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AGARDograph No. 160

AGARD Flight Test Instrumentation Series
Volume 3
on
The Measurement of Fuel Flow

by

J.T.France

NORTH ATLANTIC TREATY ORGANIZATION

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SPECIAL NOTE

Volumes 1 and 2 of AGARDograph No.160, the AGARD Flight Test Instrumentation Series, have not yet been published. They should appear before the end of 1972, and will be distributed to recipients of Volume 3.

AGARD-AG-160
Volume 3

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AGARDograph No.160 Vol.3

THE MEASUREMENT OF FUEL FLOW

by

J.T.France

Volume 3

of the

AGARD FLIGHT TEST INSTRUMENTATION SERIES

Edited by

W.D.Mace and A.Pool

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PREFACE

Soon after its foundation in 1952, the Advisory Group for Aeronautical Research and Development recognized the need for a comprehensive publication on flight test techniques and the associated instrumentation. Under the direction of the AGARD Flight Test Panel (now the Flight Mechanics Panel), a Flight Test Manual was published in the years 1954 to 1956. The Manual was divided into four volumes: I. Performance, II. Stability and Control, III. Instrumentation Catalog, and IV. Instrumentation Systems.

Since then flight test instrumentation has developed rapidly in a broad field of sophisticated techniques. In view of this development the Flight Test Instrumentation Committee of the Flight Mechanics Panel was asked in 1968 to update Volumes III and IV of the Flight Test Manual. Upon the advice of the Committee, the Panel decided that Volume III would not be continued and that Volume IV would be replaced by a series of separately published monographs on selected subjects of flight test instrumentation: the AGARD Flight Test Instrumentation Series. The first volume of this Series gives a general introduction to the basic principles of flight test instrumentation engineering and is composed from contributions by several specialized authors. Each of the other volumes provides a more detailed treatise by a specialist on a selected instrumentation subject. Mr. W.D.Mace and Mr. A.Pool were willing to accept the responsibility of editing the Series, and Prof. D.Bosman assisted them in editing the introductory volume. AGARD was fortunate in finding competent editors and authors willing to contribute their knowledge and to spend considerable time in the preparation of this Series.

It is hoped that this Series will satisfy the existing need for specialized documentation in the field of flight test instrumentation and as such may promote a better understanding between the flight test engineer and the instrumentation and data processing specialists. Such understanding is essential for the efficient design and execution of flight test programs.

The efforts of the Flight Test Instrumentation Committee members and the assistance of the Flight Mechanics Panel in the preparation of this Series are greatly appreciated.

T.VAN OOSTEROM
Member of the Flight Mechanics Panel
Chairman of the Flight Test
Instrumentation Committee

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THE MEASUREMENT OF FUEL FLOW

by

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SUMMARY

This paper discusses the main methods of fuel flow measurement and advises the prospective user of the factors that should be considered in deciding which type of meter to use and what precautions to take in the installation. Details are given of the three main types of flowmeter in common use, namely: Turbine, Orifice and Angular Momentum True Mass. The theory of operation of each type of flowmeter is given together with details of accuracy, pressure drop, susceptibility to inlet and outlet conditions, form of output, and other key parameters likely to influence the choice of type of meter to be used. A quick reference summary is provided for the comparison of the performance of the three types of meter and various methods of calibrating flowmeters are discussed.

The final chapter of the paper is devoted to specialist flowmeters which are not in general use, but may have an application in flight test work. Particular emphasis is placed on solid state flowmeters which, due to the need to obtain improved life and reliability, are the subject of much research work.

1. INTRODUCTION

Measurements of fuel flow are required during trials to determine engine performance and in particular Specific Fuel Consumption. In normal aircraft useage flow rate indication is used to set up and monitor engine performance, and a fuel consumed indication is used as a comparison with the fuel quantity gauging system. Fuel flow measurements are invariably required in mass units as the calorific value of fuel is proportional to mass not volume. In flight test programmes, the mass is often determined based on measurements of fuel volume and temperature.

This AGARDograph discusses the main types of fuel flowmeters in current use, namely:

(i) Turbine

(ii) Variable Orifice

(iii) Angular Mom ntum True Mass

and considers the advantages and disadvantages of each type.

The theory of operation is given together with details of accuracy, pressure drop, susceptibility to inlet and outlet conditions, form of output and other key parameters likely to influence the choice of meter to be used. The emphasis throughout is on practical considerations and wherever possible performance figures of typical aircraft flowmeters are quoted.

Comparison of the three types is summarised in Chapter 5 which also shows why the turbine transmitter continues to be widely used in flight test work despite the fact that it has been largely replaced in operational aircraft useage by the variable orifice and angular momentum true mass devices.

Chapter 6 is devoted to a brief discussion on the methods of calibrating flowmeters and the final chapter is devoted to those flowmeters at present under development, which may well find a use on the next generation of aircraft. Emphasis has been placed on solid state flowmeters which due to their potential to achieve improved life and reliability are the subject of much research work.

2. TURBINE FLOWMETERS

2.1 Introduction

In general aviation use where the normal requirement is to measure mass flow rate, the turbine flowmeter is losing popularity as it requires ancillary density measuring equipment to provide the necessary output. In flight test work, however, where fuel density is readily available the turbine meter still represents by far the most widely used form of flowmeter. It has the advantage of being light, compact and simple, and a wide variety of devices are available to cover virtually every application. Its mechanical simplicity, perfect running balance and low bearing loads result in unsurpassed repeatability, and it has a superior transient response to that of its main contenders.

2.2 Method of Operation

The theory of operation of the turbine transmitter is extremely complex if a full analysis under all flow conditions is required, but for operation under turbulent conditions a simplified analysis yields results which will indicate the approximate speed of rotation.

The turbine may be considered as a screw which is rotated by the fluid flow.

Referring to Figure 1.

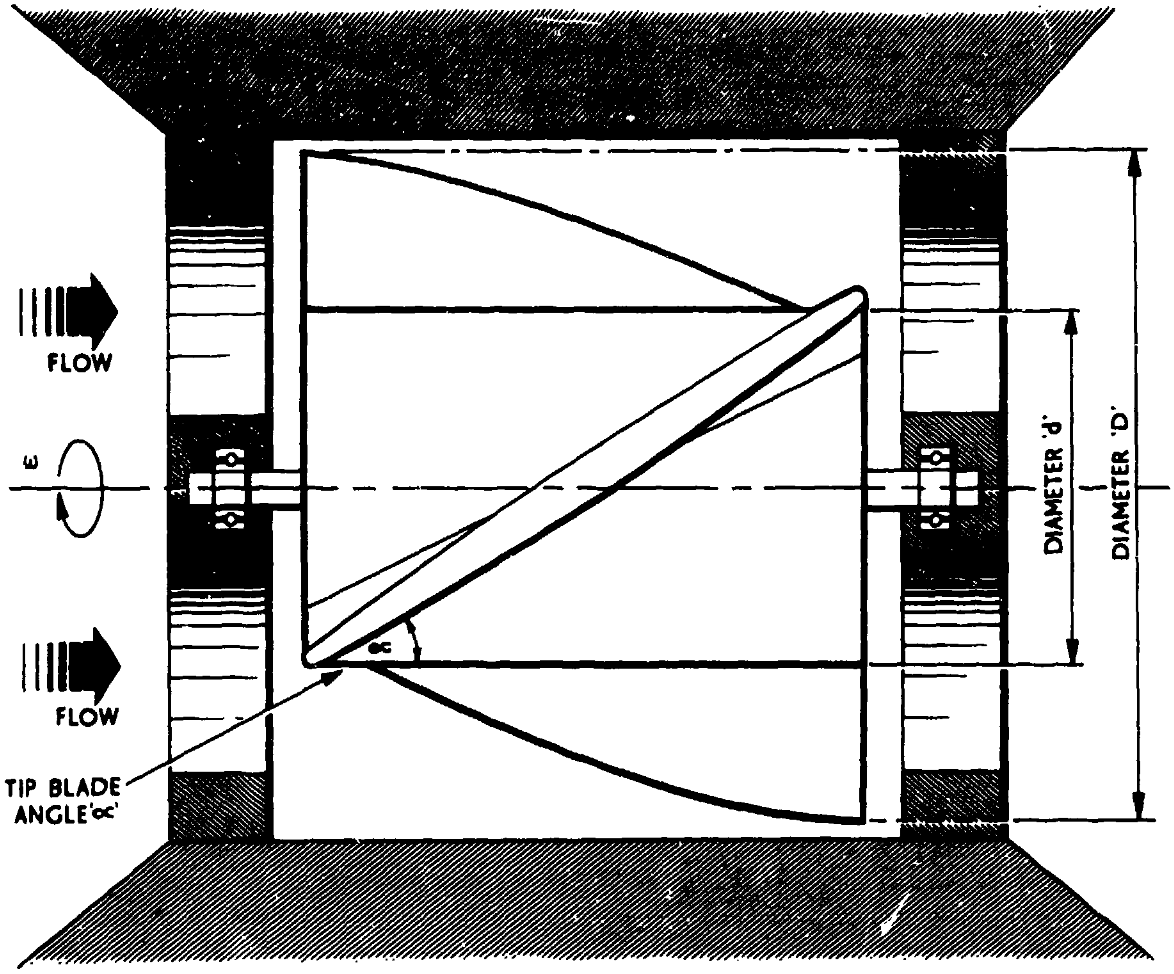


Fig. 1 Principle of Operation of Turbine Transmitter

Pitch P	=	$\frac{\pi D}{\tan\alpha}$
where D	=	outer diameter of turbine
α	=	Tip blade angle
velocity of fuel V	=	$\frac{Q}{A}$
where Q	=	Volumetric flow rate
A	=	Annulus through which fuel flows
Now A	=	$\frac{\pi}{4}(D^2 - d^2)$
where d	=	hub diameter of turbine

Now the turbine will complete one revolution as the fluid stream moves through a distance equal to the blade pitch.

$$\therefore \quad \text{Rotational velocity } \omega = \frac{V}{P}$$

$$= \frac{4Q\tan\alpha}{\pi^2 D(D^2-d^2)}$$

If Q is expressed in gallons per hour,

D is expressed in inches,

d is expressed in inches,

$$\text{r.p.m.} = \frac{1.86\ Q\tan\alpha}{D(D^2-d^2)}$$

This formula can be used to predict the speed of rotation of any turbine transmitter, usually to within ± 5%, if the relevant dimensions are known.

Various methods of measuring turbine speed are employed, the most common being to use the rotating blades to change the reluctance of a magnetic circuit which exists between pick off coils mounted on the body of the transmitter. The output from the coils is a sine wave, the frequency of which is proportional to the speed of rotation of the turbine.

2.3 Transmitter Construction

Figure 2 shows a transmitter used for flow rates up to 2,000 gallons per hour (approximately 7,000 Kg. per hour).

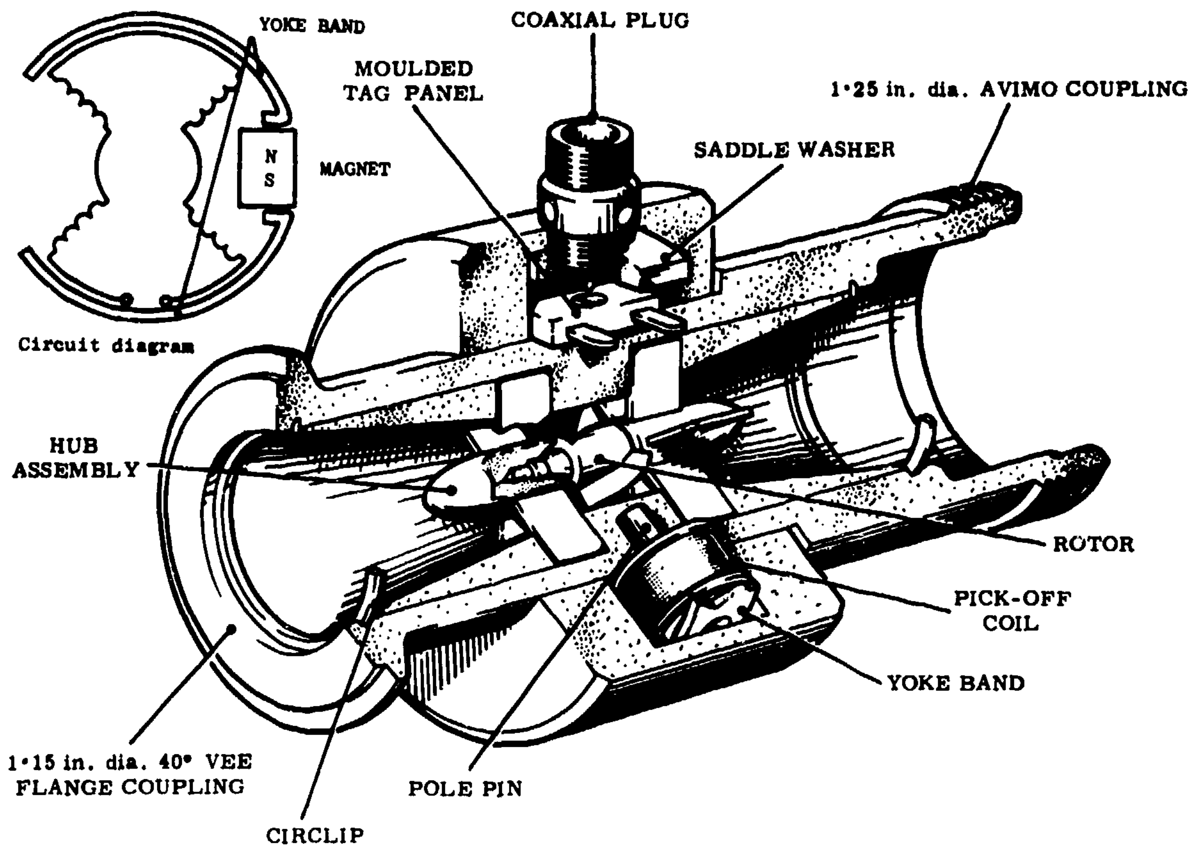


Fig. 2 Construction of Turbine Transmitter

The transmitter consists of a tubular pipe section of light alloy within which is concentrically mounted a three blade rotor of magnetic stainless steel. The rotor rotates freely in two miniature stainless steel ball races housed in identical hub assemblies.

Mounted around the periphery of the pipe section and in the same plane as the rotor are four electrical pick off coils with their associated soft iron pole pins and a permanent magnet. As the rotor revolves the reluctance of the magnetic circuit is changed and a sinusoidal wave form is induced, the frequency of which is equal to the speed of rotation of the rotor multiplied by the number of blades, in this case three.

This transmitter has an output of approximately 300 Hz at maximum flow rate, but this is low by normal standards, 1 KHz being a more typical figure.

2.4 Transmitter Performance

2.4.1 Accuracy

Figure 3 shows the calibration limits for the transmitter described in Section 2.3. The shape of the curve is representative for transmitters of this type.

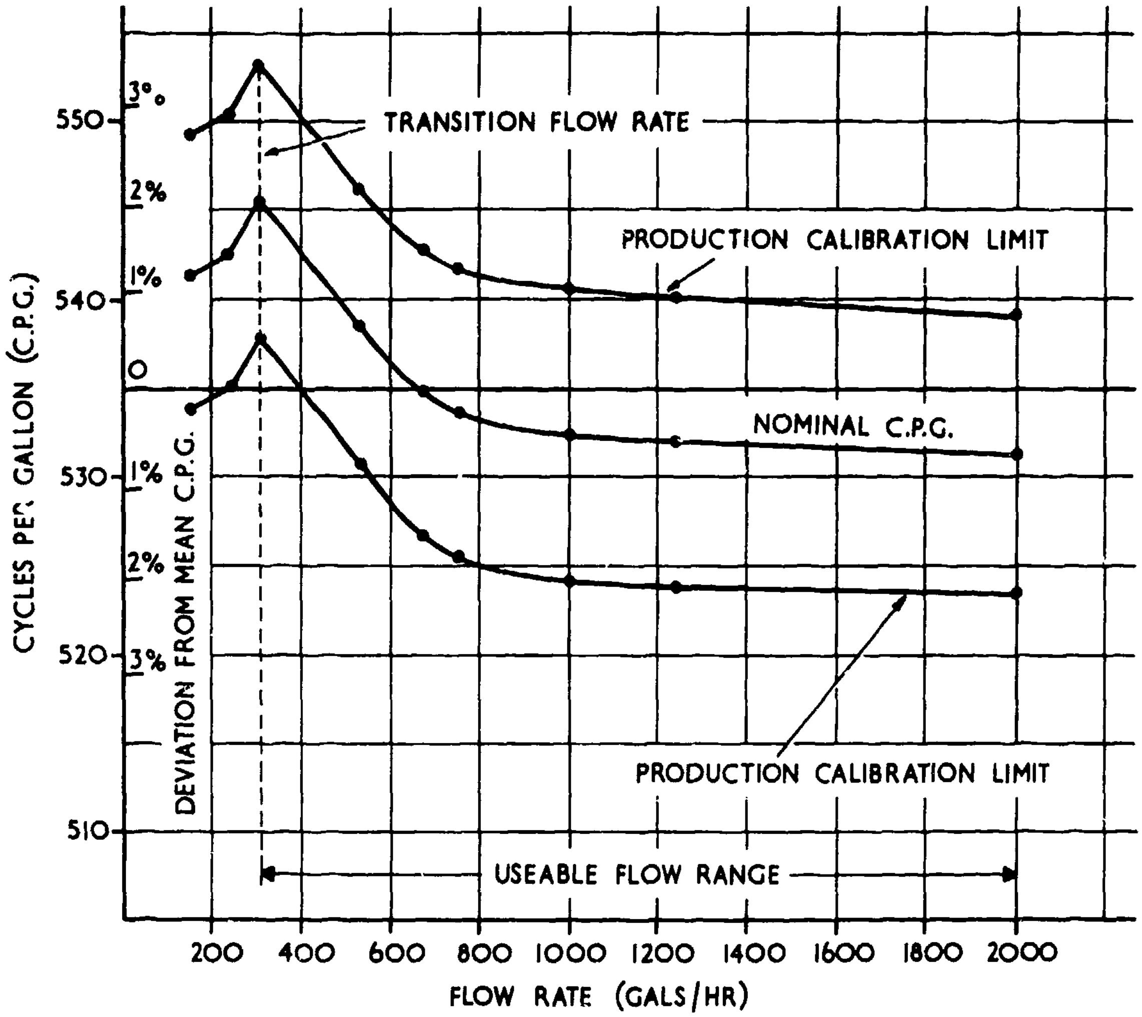


Fig. 3 Calibration Limits for Turbine Transmitter

The calibration is not linear (nominal cycles per gallon differs from the mean by +2% -1%) and shows a significant hump at the lower end of the flow range. This is due to viscosity effects and can be compensated for (Ref. 1) but this is not normally done on flowmeters used in aircraft.

The calibration shown is applicable at normal room temperatures only. At extreme fuel temperatures the limits must be extended by a further 2%.

The non linear calibration, the large spread from transmitter to transmitter, and the relatively large temperature co-efficient make the turbine transmitter unsuitable for normal service, i.e. in the large flow and temperature ranges experienced in modern aircraft. The turbine transmitter has, however, one major advantage over all other types, this being repeatability. From run to run it should be better than 0.1% as long as the transmitter has not exceeded its maximum speed and its bearings have not been disturbed.

The turbine transmitter is invariably used for flight test work where repeatability is of prime importance. Limitations expressed above can be overcome as follows:

(a) The non linear nature of a calibration curve can be taken into account in the analysis phase.

(b) Viscosity and temperature effects can be accounted for by calibrating the transmitter prior to the trial, over the range of expected fuel temperatures (at increments of 10°C or 20°C depending on the accuracy requirement) and with the different types of fuel likely to be used. It should be noted that the temperature co-efficient of a turbine transmitter is often not linear and it is, therefore, not sufficient to obtain calibration figures merely at the extremes of the fuel temperature range, if accuracies better than 0.5% are required.

As repeatability deteriorates in the laminar flow range it is usual to select a transmitter having a 'transition flow rate' below the minimum flow at which measurements are required during the course of the trial, it is also inadvisable to

exceed the maximum stated flow rate of the transmitter as this can lead to a rapid deterioration of the bearings. (These limitations if applied to the transmitter calibration shown in Figure 3 limit the useable flow range to approximately 10 to 1.)

(c) It is usual in a flight test establishment to check transmitter calibrations on a routine basis, say at 3 monthly intervals, but if critical trials are taking place then it is recommended that the transmitter be checked every 5 or 6 flights. If the transmitter has been over-speeded or the bearings have been disturbed then the unit should be re-calibrated without fail.

If the above precautions are taken then it is possible to measure volumetric flow to an accuracy of 0.2 or 0.3% of actual flow rate.

2.4.2 Life and Reliability

Being extremely simple the turbine transmitter has a high reliability and a mean time between failures of over 10,000 hours should be achievable.

Life is determined by bearing wear. Journal bearings will in general give a lower life than ball races whereas hydrodynamic bearings will give a longer life.

There are a number of methods of detecting bearing wear, two simple ones which can be carried out by monitoring the output of the transmitter with an oscilloscope during calibration runs being:

(a) The output wave form is amplitude modulated.

(b) The base line of the wave form is not constant and exhibits steps every few cycles.

Transmitters exhibiting either of the above faults are likely to give an erratic output and should be [illegible].

2.4.3 Pressure Drop

The pressure drop will obviously be largely dependent on the diameter of the transmitter and whether a diverging outlet section has been provided to aid pressure recovery. In general turbine transmitters exhibit a low pressure drop and are suitable for use in low pressure lines.

The transmitter described in Section 2.3 has a pressure drop of 1 lb/sq in at a flow rate of 2,000 galls/hr with the rotor free, but if the rotor should become jammed the pressure drop increases to 6 lb/sq in.

2.4.4 Transient Response

One of the main reasons why turbine flowmeters are used in flight test work is that they provide an excellent means of measuring flow under transient conditions.

The dynamic response of the turbine transmitter will vary according to the construction used and will generally be non-linear (Ref. 2). In general the dynamic response can be approximated by a first order-system with a time constant of about 10 millisec.

2.5 Installation

2.5.1 Effects of Flow Conditions

The turbine transmitter is affected by changes in velocity profile of the fuel and also swirl. Experimental tests have shown that changes in calibration of up to 5% can occur with certain transmitters by changing the pipework immediately upstream of the transmitter, and it is therefore essential that calibration runs are performed using representative pipework unless the transmitter is fitted with flow straighteners.

A number of establishments have successfully fitted flow straighteners to the inlets of their transmitters but the work is not well documentated. One approach adopted is to provide a honeycomb structure, the length of which is at least 10 times the diameter of each cell. This virtually eliminates calibration shifts of changing pipework but doubles the pressure drop across the transmitter. It has also been found that if the flow straightener is disturbed then calibration shifts occur, so it is advisable that the straightener be made an integral part of the transmitter.

2.5.2 Calibration Adjustments

In flight test work it is not normal to adjust the calibration of a turbine flowmeter, any divergencies from the nominal output of the unit being taken into account in the trials analysis.

If for any reason specific calibration is required then minor shifts can be obtained by deflecting the rotor blades to change the pitch angle or by removing metal from the blades. This procedure is not recommended except under exceptional circumstances as the alignment of the transmitter may well be disturbed.

2.5.3 Aircraft Wiring

As the turbine transmitter requires no external power source the aircraft wiring is very simple and only 2 wires are required. These should be shielded or twisted together, to avoid electro-magnetic interference.

2.5.4 Orientation

Turbine transmitters are not normally attitude sensitive, but journal bearings may give problems under certain circumstances and should be avoided.

2.6 System Implementation

2.6.1 Density Measurement

Density measurement is required to modify the output of the turbine flowmeter, which is proportional to volumetric flow, to obtain mass flow.

For flight test work, where accurate measurement is of paramount importance, it is normal to take a sample of the fuel to be used and measure the specific gravity in the laboratory using a hydrometer. If care is taken using this method the specific gravity of the fuel can be determined to an accuracy of ± 0.1%.

The temperature of the fuel entering the transmitter must be monitored on the aircraft. This is done by placing a temperature sensitive resistor or a resistance bulb thermometer in the fuel line immediately up-stream of the transmitter. Temperature measuring devices are available with an accuracy of ± 1°C, which represents a change in density of ± 0.1%.

Using a turbine transmitter and a temperature sensing bulb, mass measurements can be made to an accuracy of better than ± 0.5% over the full flight regime experienced in normal flight trials work.

Airborne densitometers are available working on a number of principles, one being that of Archimedes. A float is arranged such that it rises or falls dependent on the density of the fuel in which it is immersed. Complicated stabilising arrangements are required if the system is required to work under all conditions of aircraft acceleration and attitude.

Another approach is dependent on the fact that if a vessel containing fluid is subject to an oscillatory force, its displacement will be a function not only of the mass of the vessel itself, but also of the density of the fluid contents. A number of attempts have been made to produce a practical

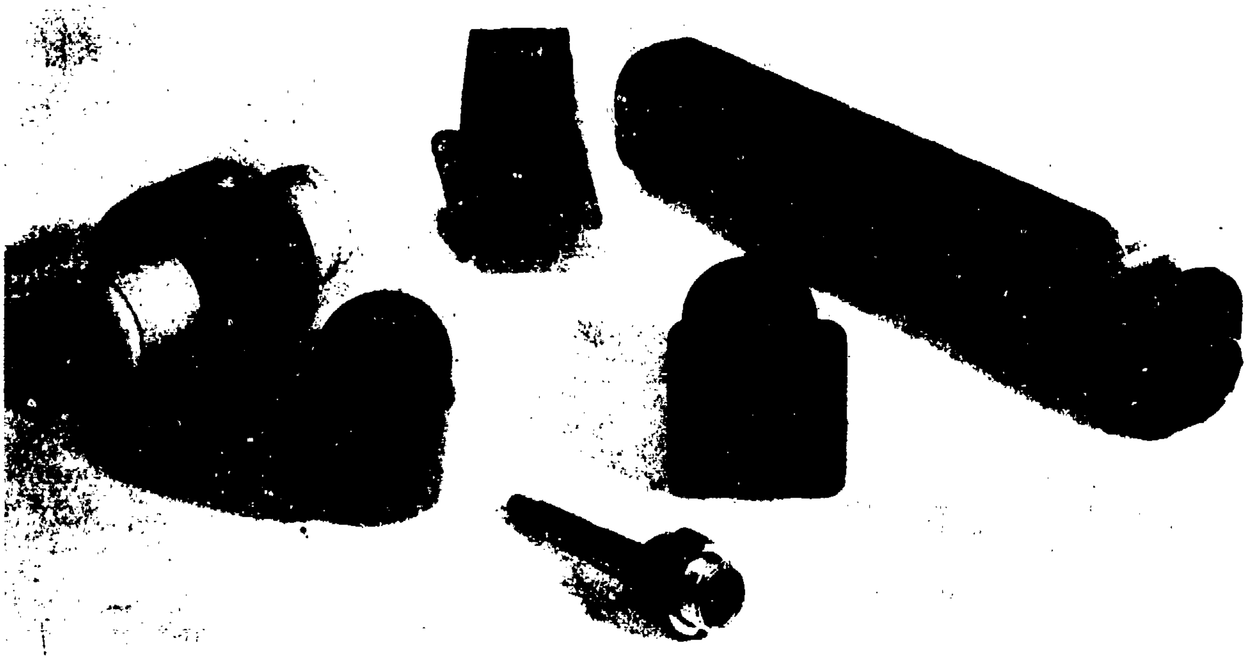


Fig. 4 Turbine Flowmeter System

densitometer working on this principle, but have generally been unsuccessful, the device being extremely susceptible to vibration and changes of temperature. An improved vibration densitometer is now available having an accuracy of better than 0.5% of full scale over normal fuel temperatures, but no service experience is, as yet, available (Ref. 3).

Densitometers have been produced which measure the dielectric constant of the fuel passing through the transmitter. This is an application of the widely used aircraft capacitance contents gauge, which has the following limitations:

(i) The ratio of dielectric constant to density varies by approximately 3% over the temperature range -55°C to +55°C and therefore if density is required to a high degree of accuracy fuel temperature must be measured and the densitometer output corrected.

(ii) The ratio of dielectric constant to density can vary from sample to sample of any fuel by up to 1%, and this cannot be compensated for.

A number of aircraft at present in service are provided with a manual density corrector, the fuel density being set on a dial by the ground crew whenever the aircraft is re-fuelled.

2.6.2 Basic System Signals

The output of a turbine transmitter is normally a sine wave, the frequency of which is proportional to flow rate. A frequency to D.C. converter is therefore normally used to obtain a flow rate indication, whilst fuel used is obtained by counting the number of cycles from the transmitter on an impulse counter. These functions can be computed to an accuracy of approximately ±0.5% using airborne computers, but it is normal in flight test work to carry out this process as part of the analysis programme, in which case the errors introduced will be negligible.

Figure 4 shows a typical system employing manual density correction.

3. VARIABLE ORIFICE FLOWMETERS

3.1 Introduction

The major drawback of the turbine flowmeter for applications where mass flow is required is that the basic output is volumetric flow, not mass flow and a separate density corrector is required. The variable orifice flowmeter represents a means of obtaining an output, which although not directly proportional to mass, is adequate for those applications where an accuracy of 1.5% of point of mass flow rate is acceptable.

A number of means of instrumentation are available but all depend on measuring the pressure difference across a variable orifice. Details will be given below of two types of flowmeter fitted in operational aircraft, whilst a brief description of the 'Rotameter' system is provided in Section 6.3.

3.2 Method of Operation

The relationship between pressure and velocity in a moving fluid is covered by Bernoulli's Equation, the derivation of which can be found in most standard texts on Fluid Mechanics.

Bernoulli's equation states:

$$\rho \frac{V^2}{2} + P = P_o \qquad \text{(i)}$$

or

$$V = \sqrt{\frac{2(P_o - P)}{\rho}} \qquad \text{(ii)}$$

where P_o = Total or stagnation pressure

P = Static pressure

ρ = Fluid density

V = Flow velocity

Now the mass flow $\dot{M}$ through any area is given by:

$\dot{M}$ is proportional to $AV\rho$

where A = area

In the case of an orifice the effective area is reduced by a factor C where:

C = orifice discharge coefficient

and the equation thus becomes:

$$\dot{M} = ACV\rho \qquad \text{(iii)}$$

Substituting the value of V from equation (ii)

$$\dot{M} = AC\sqrt{2\rho(P_o - P)}$$

$$= AC\sqrt{2\rho h}$$

where h = pressure drop between an upstream point and the minimum cross sectional area of the flow path, known as the vena contracta.

The equation may be re-written:

$$h = \frac{\dot{M}^2}{2\rho A^2 C^2} \quad \text{...(iv)}$$

The measurement of the pressure drop across an orifice represents a simple method of flow measurement, but there are major reasons why the approach is not suitable for use as an aircraft flowmeter. For accurate measurement it is necessary to maintain turbulent flow conditions over the flow range to be measured and this entails keeping the Reynolds number well above 10^4 (Ref. 4). If we reduce the diameter of the orifice to obtain turbulent conditions at the low flow rates then the pressure drop at high flow rates becomes excessive. Reference to equation (iv) shows that pressure drop is proportional to mass flow rate squared, so for a flow range of 20 to 1 we require a pressure range of 400 to 1, which would be unacceptable in an aircraft fuel system. If fixed orifice flow meters have to be used, it will be necessary to restrict the flow range to 5 or 10 to 1. In that case accuracies to the order of 1% can be obtained.

The limitations of the fixed orifice are largely overcome by producing a flowmeter having a variable orifice, the area of which increases with increase in mass flow. By reducing the area of the orifice at low flow rates it is possible to maintain turbulent flow, whilst by increasing the orifice area at high flow rates it is possible to maintain the pressure drop within reasonable limits. Re-writing equation (iv):

$$A = \frac{\dot{M}}{C\sqrt{2\rho h}} \quad \text{...(v)}$$

Let x be the relative displacement of two members forming a variable orifice so designed that the area A varies linearly with x, then if x is continuously changed in such a way that h remains constant it becomes a measure of the quantity $\dot{M}$. It can be seen that devices of this type provide an output that is dependent on the square root of density and the device has therefore gone some way towards giving an output proportional to mass flow rate.

Compensation for density changes with temperature is usually achieved either by a bimetallic element controlling a secondary orifice or by a temperature sensitive component in the electrical circuitry of the flowmeter.

Variations of C with flow rate may be compensated for by shaping empirically the components forming the orifice, but variation of C with temperature is also inevitable since it depends in part upon Reynolds Number which will change with density and viscosity. These effects may be reduced by keeping Reynolds Number high, but this is not easily achieved. This class of flowmeter, therefore, provides a spacious field for the exercise of empirical cunning, but it does not appear to be possible to predict from simple theory the chances of success for any particular proposal. Nevertheless the principle is used in three well known forms of flowmeter, namely the Rotameter which is employed as a secondary standard in flowmeter calibration (see Section 6.3), the Negretti and Zambra Flowmeter and the Bendix Spring Restrained Vane Flowmeter.

The Negretti and Zambra Meter contains a tapered plug which protrudes through the orifice, the position of the plug being determined by a hydraulic servo which is designed to maintain a constant pressure drop across the orifice.

A detailed description of the Spring Restrained Vane Flowmeter is given below, together with a brief introduction to the Negretti and Zambra Flowmeter.

3.3 The Spring Restrained Variable Orifice Flowmeter

3.3.1 Method of Operation

The method of operation of this type of flowmeter can be described by reference to Figure 5.

Fuel enters the metering assembly which consists of a measuring vane rotating within a shaped chamber. The vane is mounted on a shaft which is supported at each end by a bearing. Displacement of the vane is caused by pressure of the fuel on the vane surface, the angular displacement being controlled by a spiral spring with a constant spring rate. The outer edge of the vane and the chamber will form an orifice, the area of which is proportional to x and which increases with angle Θ. The relationship between x and Θ is nominally linear, but the characteristic is empirically adjusted in the design phase to obtain a linear relationship between the angular position of the vane Θ and the mass flow rate divided by the square root of density.

By mounting a position transducer such as a synchro or a potentiometer on the shaft of the vane, the angular position of the vane is converted to an electrical signal, the magnitude of which is therefore proportional to mass flow rate divided by the square root of density.

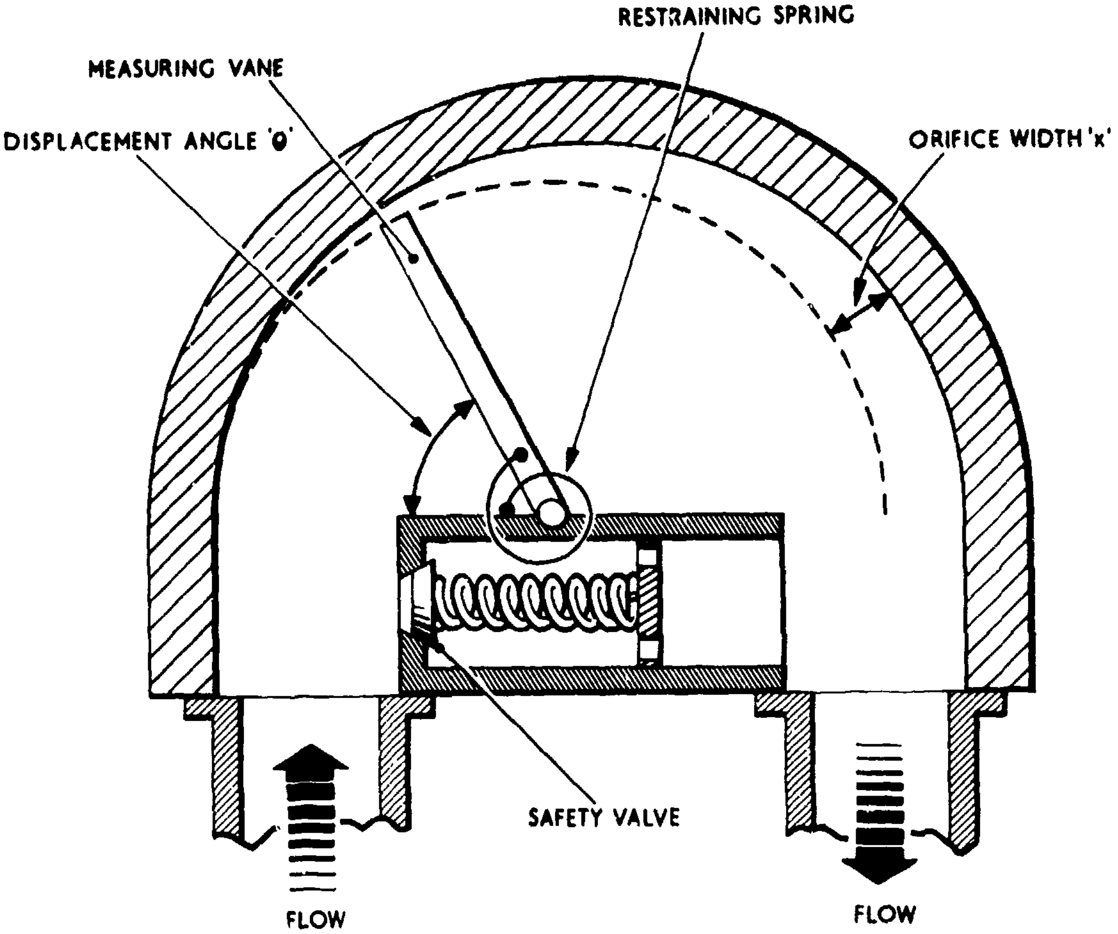


Fig. 5 Principle of Operation of Variable Orifice Transmitter

Temperature sensitive resistors mounted so as to sense fuel temperature are connected to the electrical transducer in such a way as to compensate for changes in fuel density with temperature. This compensation is not precise, and the temperature range of the transmitter must therefore be limited.

To prevent fuel starvation to the engine a by-pass valve is provided which will open if the vane should become jammed in the closed position. The valve is set to open at a pressure approximately twice that of a normal pressure drop across the vane.

3.3.2 Transmitter Construction

Figure 6 shows the construction of a typical flowmeter.

The body of the transmitter consists of an approximately cylindrical casting having two ports for fuel line connections. The casing houses an insert which has been machined on its inner surface to form one wall of the variable orifice.

The moving vane is balanced and damped by the provision of a counter weight which moves in a chamber filled with static fuel. The restraining spring is manufactured from Ni Span C (see paragraph 4.3.2).

To avoid the use of a rotating seal between the fuel chamber and the electrical compartment, which houses the potentiometer, shaft position is transmitted by means of a magnetic coupling.

During manufacture the electrical compartment is filled with a fluid such as Electrolube 2 to provide damping for the potentiometer wiper, which will be subjected to extremely high levels of vibration on an engine mounted transmitter (typically 10 g.).

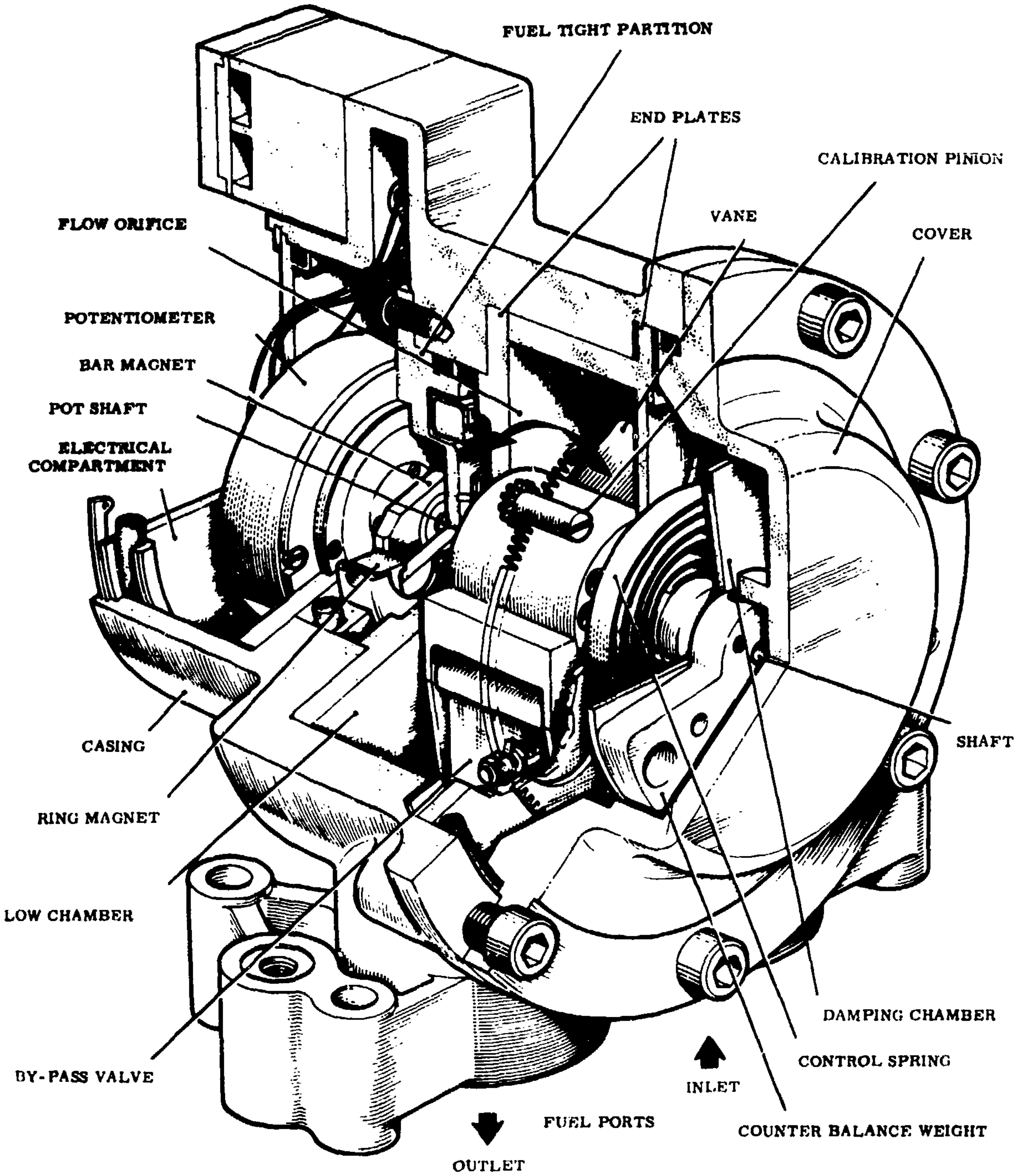


Fig. 6 Construction of Spring Restrained Variable Orifice Transmitter

3.3.3 Transmitter Performance

3.3.3.1 Accuracy

The variable orifice transmitter gives an output proportional to mass flow divided by the square root of density.

Correction is incorporated in the transmitter to accommodate changes in density with temperature, but changes in density due to the use of differing fuels is not compensated for. At room temperature Avtag has a specific gravity of 0.745, whilst that of Avtur is 0.79. The change in ρ is therefore approximately 6%, and should lead to a change in transmitter output of 3%, but tests show that the change in transmitter output between these fuels in practice is less than 0.5%. This can be explained by the fact that the denser fuel also has the higher viscosity and the discharge co-efficient of the orifice is therefore reduced, thus increasing the pressure drop across the orifice. Errors due to change in density are thus reduced.

In order to achieve a high accuracy in transmitters of this type extremely close control of dimensions in the fuel chamber must be maintained and the leakage paths which allow fuel to pass through the transmitter by any means other than through the orifice must be eliminated. Failure to eliminate such leakage introduces errors which are particularly noticeable at the lower flow rates where the area

of the orifice is at a minimum.

Practical flowmeters also show a deterioration of accuracy towards the upper limit of the flow range which is thought to be due to turbulence, though this has never been conclusively proved.

In addition to errors introduced in the flow chamber the error in converting the vane shaft position to an electrical signal must be considered. A positional error of 0.5° would be expected which is equivalent to an error of approximately 0.25% of full scale.

The construction of the transmitter is such that bearing stiction would adversely affect accuracy during calibration, so vibration is applied to introduce dither. In the aircraft environment stiction is overcome due to the presence of engine vibration.

Figure 7 gives calibration limits for a modern variable orifice flowmeter. In the cruise range an accuracy of 1.3% of point* is achieved for normal fuel temperatures whilst under adverse conditions 1.7% is achieved. The figure illustrates clearly the rapid deterioration in accuracy at the lower end of the flow range, though it should be noted that the transmitter illustrated has a flow range of 25 to 1 which is larger than is normally expected for this type of device.

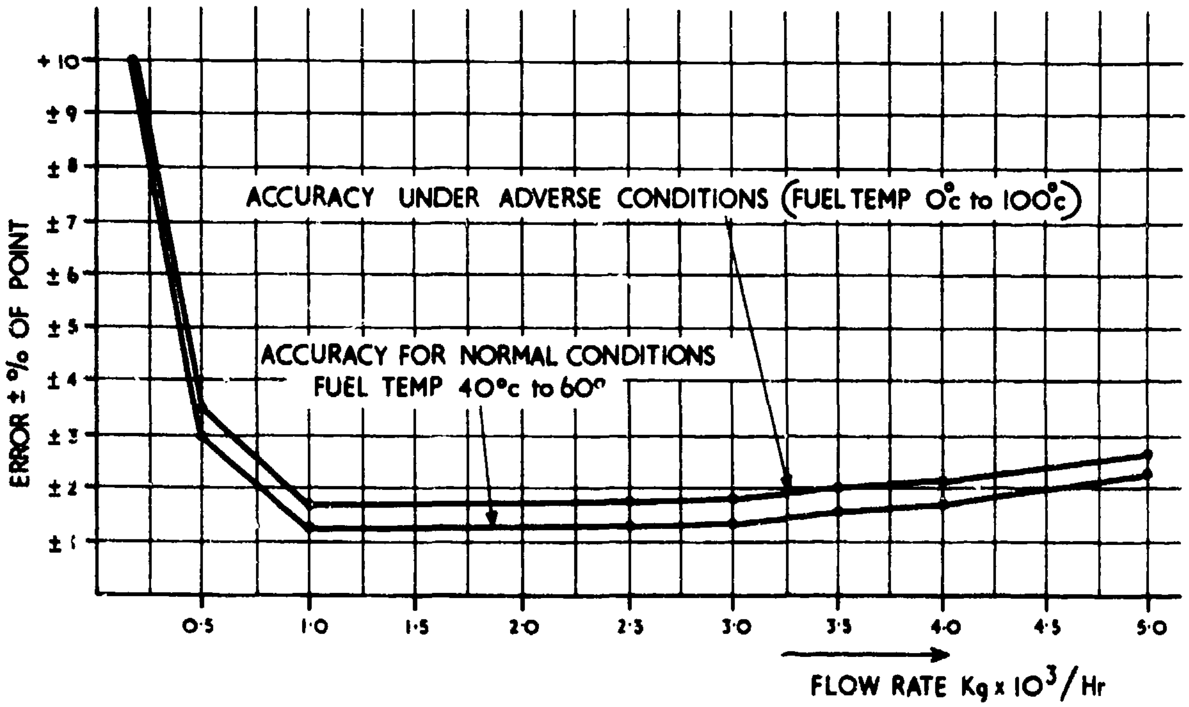


Fig. 7 Calibration Limits for Spring Restrained Variable Orifice Transmitter

3.3.3.2 Life and Reliability

The only wearing parts in the fuel chamber are the vane shaft bearings and these are moving only during changes in flow rate.

The dominant factor determining the life of the transmitter is the electrical transducer, whether it be a synchro or a potentiometer. Significant improvements have been made in these components in recent years, but a mean time between failures of 3,000 hours is typical.

3.3.3.3 Pressure Drop

The pressure drop across this type of flowmeter is in general higher than for a turbine type covering the same flow range.

Typical pressure drop for a transmitter having a maximum flow range of 10,000 Kg/Hr would be 4 lb per square inch under normal operating conditions. With the fuel chamber blocked the safety valve will open, limiting the pressure drop to 8 lb per square inch.

3.3.3.4 Transient Response

The author is not aware of any detailed experimental work in this field. Simple tests show that the transmitter described in Section 3.3.2 has a rise time of approximately 50 millisec when subjected to a step change of flow equal to the maximum flow rate of the device. This is thought to be typical for devices of this type.

* '% of point' is synonymous with '% of actual flow' throughout this AGARDograph.

3.3.4 Installation

3.3.4.1 Effects of Flow Conditions

The variable orifice transmitter is, like the turbine, particularly sensitive to flow conditions and calibration should be carried out with representative pipework.

3.3.4.2 Calibration Adjustments

Calibration is adjusted by setting the length of the spring to give the correct rate adjustment, adjusting the position of the potentiometer to give zero shift and obtaining the final trimming by means of variable resistors which are placed in series with the potentiometer.

3.3.4.3 Aircraft Wiring

Three wires are required to the transmitter. As the signal is of a relatively large magnitude and the source impedance is low, shielded wires are not required.

3.3.4.4 Orientation

The transmitter vane is balanced so the device is not attitude sensitive.

3.3.5 System Implementation

The flow rate indicator contains a simple regulator circuit driven from the aircraft 28V d.c. supply. The regulated supply is used to energise the transmitter potentiometer and is also used to energise the fuel consumed indicator.

The voltage on the wiper of the transmitter potentiometer is passed via a buffer amplifier to a moving coil movement which displays flow rate, or to suitable recording equipment.

The flow rate signal, after passing through the buffer amplifier, is routed to the fuel consumed indicator. This indicator contains a Miller Integrator which integrates the flow rate signal, which is then chopped to drive an impulse counter. Integration errors are typically 0.5%

The indicators in this system utilise d.c. analogue circuitry and care must therefore be taken to minimise drift.

Fig. 8 Variable Orifice Flowmeter System
(Approx. ½ full size) - Courtesy Elliott Flight Automation Ltd.

Utilising the transmitter accuracies quoted in Section 3.3.3.1, a typical system accuracy summary will be as follows:

Operating Conditions	Fuel Used Error %	Flow Rate Error %
Normal	1.5	2.0
Adverse	2.0	2.5

Figure 8 shows an engine channel of a flowmeter of the spring restrained variable orifice type.

3.4 The Negretti and Zambra Variable Orifice Flowmeter

3.4.1 Description and Operation

Reference should be made to Figure 9.

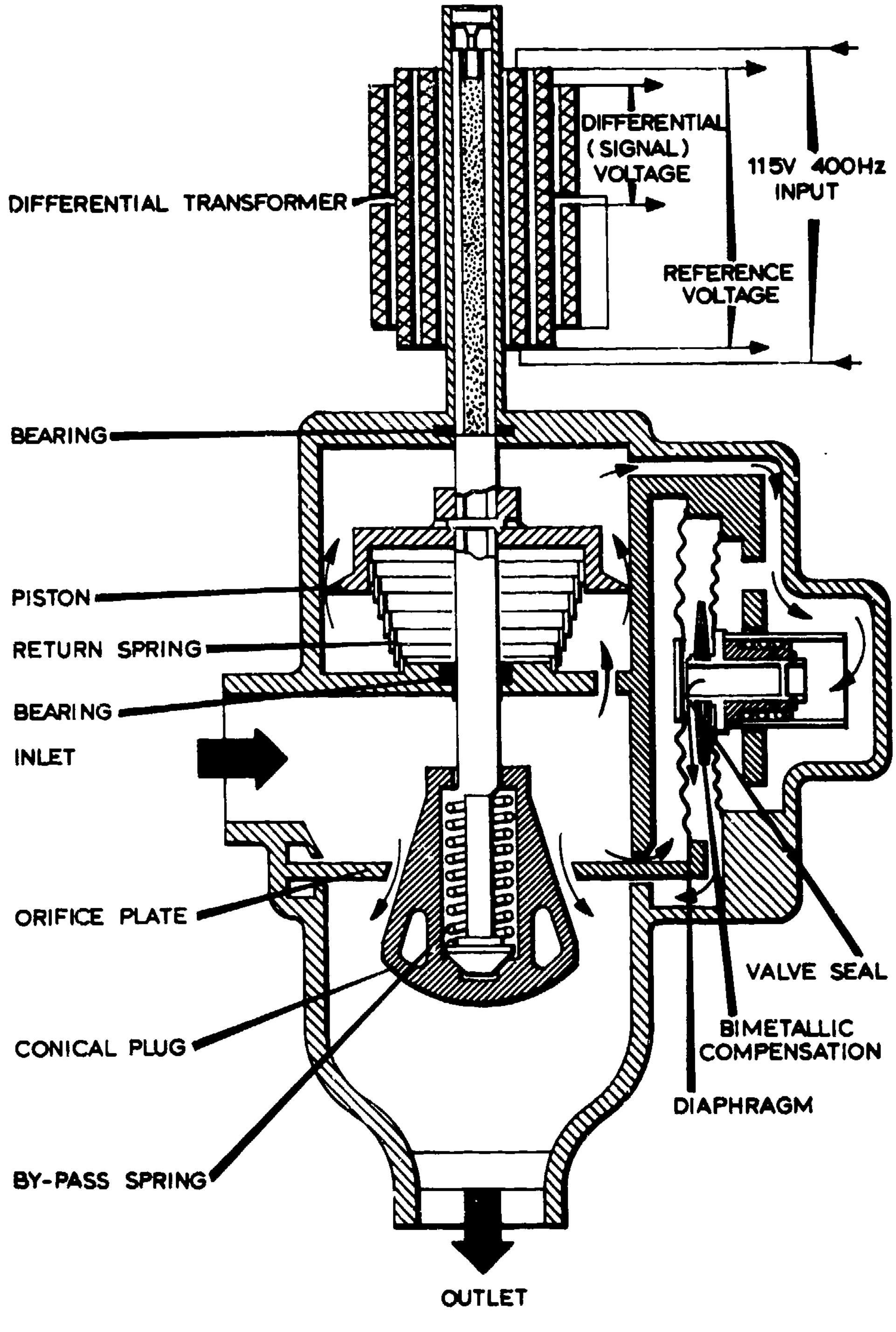


Fig. 9 Principle of Operation of Negretti & Zambra Flowmeter
Courtesy Negretti & Zambra (Aviation) Limited

Consider the situation as fuel starts to flow. A pressure difference will develop across the orifice resulting in the diaphragm and valve being moved towards the valve seat. The movement will continue until the valve is closed, thereby stopping the by-pass flow. The pressure acting on the area of the conical plug will then cause the rod assembly to move downwards, so increasing the area of the annulus at the orifice. This movement will continue until the pressure difference across the orifice has fallen to the value at which the valve reopens and allows a flow through the by-pass.

The by-pass flow will cause a pressure difference across the piston, which is designed to provide a restricted passage for fuel, and this will increase as the valve opens until the upward force on the piston balances the downward force on the conical plug.

Any overshoot of the piston and conical plug assembly, or subsequent reduction of flow through the meter, will result in a reduction of the pressure difference across the main orifice. This will cause the diaphragm to open the valve further thus increasing the pressure difference across the piston. The piston will then move upwards until balance is restored.

Under steady conditions the piston and conical plug are servo operated into a position such that the pressure difference is constant at a value determined by the setting of the diaphragm. The position of the piston rod is therefore a measure of the amount of fuel passing the main orifice, and the relatively small by-pass flow remains sensibly constant.

Due to the servo operation the unit is capable of operating a robust transmission device and can overcome extraneous torques. The version shown has a differential transformer as its electrical transducer, and a ratio of electrical signals relating directly to the rate of flow is obtained without any mechanical linkage.

Bimetallic compensation is used to minimise the effects of fuel density change with temperature, and effects of variation in fuel viscosities are minimised by orifice design.

Overpressure relief is covered initially by the powerful servo action, but should this prove inadequate a further by-pass is made available by connecting the conical plug to the piston rod via a by-pass spring.

3.4.2 Performance

A typical accuracy for this type of flowmeter is $\pm$ 2% of actual rate for all flows from 450 Kg/hr to maximum flow rate, at fuel temperatures up to 180°C.

The flowmeter has a standard maximum metering capacity of 4,500 Kg/hr at a nominal pressure drop of 2.0 lb per square inch, however other ranges are available.

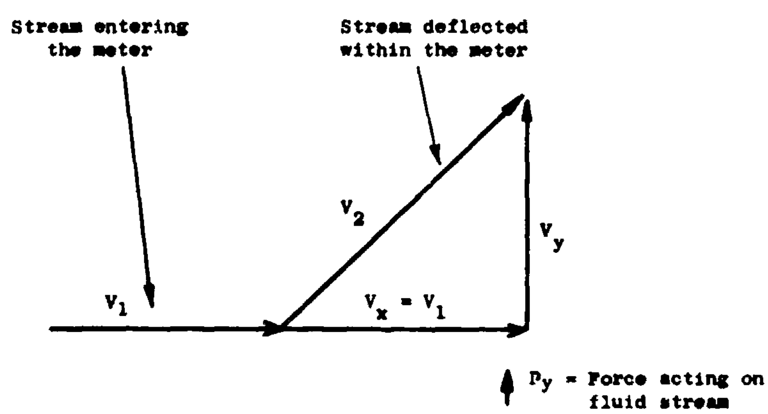
4. ANGULAR MOMENTUM TRUE MASS FLOWMETERS

4.1 Introduction

Angular momentum true mass flowmeters represent at the present time the most accurate type of flowmeter in widespread use for applications where mass measurement is required. Flow transmitters having an accuracy of better than 0.5% of point over the cruise flow range are now available and with the associated computing it is possible to obtain flow rate and fuel consumed indications having an accuracy of better than 1%.

The only true mass flowmeters at present in use in any quantity are based on Newton's Second Law of Motion, applied as the measurement of the force required to alter the velocity of the fluid stream in a known manner. It is usual in this type of instrument for the fluid to be accelerated in a direction normal to the inlet flow to a constant velocity v_y by external means which make no reference to the prevailing value of the inlet velocity v_1.

The velocity vector diagram is as follows:



The force Py acting on the fluid stream is given by

$$P_y = \frac{d}{dt} (M\, v_y)$$

where M = Mass of fuel

v_y = Component of velocity of fluid within the meter normal to the direction of entry.

If v_y is constant then:

$$P_y = v_y \dot{M} = C\dot{M}$$

4.2 Practical Systems

There are two main types of angular momentum true mass flowmeter, utilising either the stator torque or the rotor torque principle. Both types involve giving the fluid a constant rotational velocity in a direction normal to the direction of flow.

In the stator torque flowmeter the fuel is first passed through a rotating vane moving at a constant speed which imparts a constant angular rotation or swirl to the fuel. The fuel is then passed through a turbine designed to remove all angular momentum from the fluid. In doing this a torque is exerted on the turbine which is proportional to the mass flow rate of the fluid passing through the turbine. This torque is calculated by measuring the deflection of a spring which is restraining the turbine.

In the rotor torque flowmeter the fuel is first passed through straightening vanes to remove all swirl. The fuel then passes into the measurement assembly of the flowmeter which consists of a set of vanes rotating at constant speed about an axis which is coincident with the axis of the flowmeter. The torque required to drive the rotating vanes is proportional to the magnitude of the angular momentum applied to the fuel which is in turn proportional to the mass of fuel passing through the measurement assembly.

It can be seen from the above that the stator torque and rotor torque flowmeters have many similarities and it is therefore proposed to describe in detail only one variant. The rotor torque flowmeter has been selected as it is felt that this type will become increasingly important with the growing use of airborne digital computers as it provides a digital output, whereas the stator torque flowmeter usually provides an analogue signal proportional to the position of the restrained turbine.

4.3 The Rotor Torque True Mass Flowmeter

4.3.1 Method of Operation

With reference to Figure 10, fuel on entering the transmitter is passed through straightening vanes fitted into an annular space, which have the effect of removing swirl and random disturbances caused by the inlet configuration, which is unique to the particular installation. The axially flowing fuel is then passed through the measurement assembly, which is being driven at a speed of approximately 100 rpm by an electric motor or hydraulic turbine (see Para. 4.3.2).

The measurement assembly consists of the constant speed shaft on which an impeller is free to rotate on low friction bearings. Angular torque is imparted to the impeller by the shaft by means of a torsion spring, whose linear torque/rotation characteristic is known. The impeller is again a set of axial vanes spaced around an annular gap, of similar dimensions to the straightening vanes.

The effect on the fuel is as follows: After leaving the straightening vanes in a truly axial sense the fuel enters the impeller which, rotating at constant speed, imparts a fixed swirl rate to the fuel. The torque required, therefore, is proportional only to mass flow, which is proportional to angular twist of the spring.

A significant spurious effect is found from the shear force between the periphery of the rotating impeller, and the bore of the transmitter housing, (which must be a close fit to avoid excessive leakage). This effect is overcome by shrouding the impeller with a thin cylinder (normally referred to as a 'drum') which is fixed to the driving shaft. The shear force, mentioned above, is still present, but now appears as an extra torque required by the motor, which is immaterial, and not as an error torque on the impeller, the periphery of which is rotating at the same speed as the internal diameter of the drum. The drum shown in Figure 10 has been displaced from the impeller to aid clarity.

The remaining task is to measure the wind-up angle of the spring. Two magnets rotate fixed to the measurement assembly; one is on the periphery of the drum, the other is on the periphery of the impeller. When the spring is un-deflected the magnets are in line. Two pick off coils are sited on the case one above each magnet. When the measurement assembly rotates pulses are induced into the coils, which are fed through the aircraft wiring to the fuel flow computer. The time interval between the pulses is proportional to spring deflection, and hence to mass flow rate.

It has been stated above that the measurement assembly has to be driven at a synchronous speed. However, if the speed changes, for example let us assume it is reduced, the swirl rate is reduced linearly, and the spring wind-up is reduced, also linearly. Thus rotational speed and spring wind-up are directly related, and it can be shown that the resulting pulse separation from the pick-offs is still proportional to mass flow rate, and has the same law.

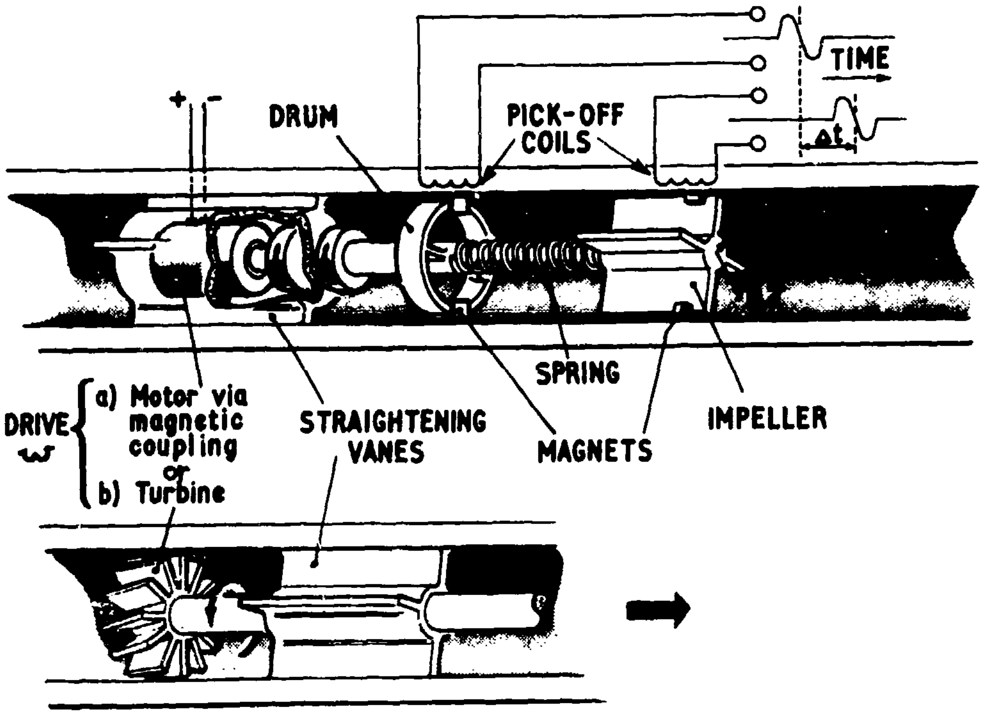


Fig. 10 Principle of Operation of Rotor Torque Transmitter

Referring to Figure 10 let the inner and outer radii of the annular fuel chamber in the impeller be R_1 and R_2 respectively.

The drum angular velocity be ω

the impeller torque be T

the angular deflection between drum and impeller be Θ

the time between drum and impeller pulses be t

and the mass flow rate be $\dot{M}$

Newtons Second Law of Motion applied to a rotating mass gives the equation

$T \propto \frac{d}{dt} (I\omega)$ ....(i)

Where I is the mass moment of Inertia which can be substituted by MK^2

where K = radius of gyration

$\therefore$ $T \propto \frac{d}{dt} (MK^2\omega)$

$\frac{dM}{dt}$ = Mass flow rate ($\dot{M}$)

$\therefore$ $T \propto \dot{M} K^2\omega$ ....(ii)

For an annulus: $K^2 = \frac{R_1^2 + R_2^2}{2}$

where R_1 and R_2 are the inner and outer radii respectively

$\therefore$ $T \propto \dot{M}\omega \frac{(R_1^2 + R_2^2)}{2}$ ....(iii)

As R_1 and R_2 are constants fixed by the physical design of the transmitter then $T = K_1\dot{M}\omega$ where K_1 includes the constant of proportionality.

If K_2 is the spring constant

then $K_2\Theta = K_1\dot{M}\omega$ ....(iv)

Now spring deflection $\Theta = \omega t$

Substituting in equation (iii) gives:

$K_2 \ \omega t = K_1 \ \dot{M}\omega$

$\therefore \quad \dot{M} \propto t$

Thus the time interval t is a direct measure of mass flow rate $\dot{M}$ and is independent of rotational speed ω.

4.3.2 Transmitter Construction

Figure 11 shows the construction of a rotor torque flowmeter designed to operate with flow rates up to 10,000 Kg/hr.

The body is machined from a high tensile aluminium alloy. The housing for the motor stator is an integral part of the body, being supported in the centre of the straightening vanes on three webs.

The measurement assembly consists of the drum and impeller coupled together by the torque sensing spring. The only source of error in the measurement assembly is some factor which affects the impeller without affecting the drum. Since both are rotating at identical speeds (except under transient conditions of flow rate) such effects as bearing friction, fuel contamination, etc. have no effect upon accuracy.

Viscous drag between the measuring impeller and the stationary body housing is eliminated by the use of the driving drum, the clearance between drum and impeller circumference being very small. The measurement assembly is balanced before assembly in the body to ensure that the transmitter calibration is insensitive to acceleration forces.

The torque required to drive the impeller is transmitted via a precision spiral spring, a method which still represents one of the most simple and accurate forms of torque sensor. The spring must be manufactured from a material which can give extremely accurate and repeatable characteristics. Suitable material is Ni Span C which is unique in that the change of Youngs Modulus of Elasticity with temperature can be set to the desired value by adjusting the heat treatment of the material.

The motor drive unit usually takes the form of an electric motor, but recent work has been directed towards driving the measurement assembly from a turbine which extracts the required energy from the fuel. The types of drive used are:

(a) A Conventional 'High Speed' Synchronous Servo Motor

This has the advantage that it can be connected directly to the aircraft 400 Hz supply and therefore does not require a special purpose power pack, but suffers from the disadvantage that it runs at too high a speed to be coupled directly to the measurement assembly and a speed reducing gear head is therefore required.

As the speed of rotation is proportional to the frequency of aircraft supply and this varies typically $\pm 5\%$, it follows that the angular velocity of the measurement assembly will not be constant. It has been shown in Section 4.3.1 that this will not affect the accuracy of the transmitter, but if it is proposed to integrate the transmitter output to obtain a fuel consumed indication, an additional computation will be required to compensate for changes in frequency of the aircraft supply.

It is possible to couple the output shaft of the gear head to the drum directly, but this involves passing the drive shaft through the motor housing, and seals to prevent ingress of fuel will be required. It is common practice to overcome this problem by using a magnetic coupling, the drive magnet being mounted on the gear head output shaft whilst the coupled magnet is mounted on the measurement assembly drum.

(b) A 'Low Speed' Motor

The low speed motor which is illustrated in Figure 11 consists of a coil wound stator which produces a rotating flux. This rotating flux couples with a permanent magnet which is mounted on the measurement assembly drum. It can be seen that this is a very simple system which does not involve the use of any moving parts within the motor housing. The deletion of the high speed motor significantly increases the life and reliability of the transmitter.

A low speed motor requires the provision of a special low frequency power supply operating at below 10 Hz. If this frequency can be accurately maintained, for example by deriving it from a crystal controlled source then the computation necessary to obtain a fuel consumed signal can be simplified.

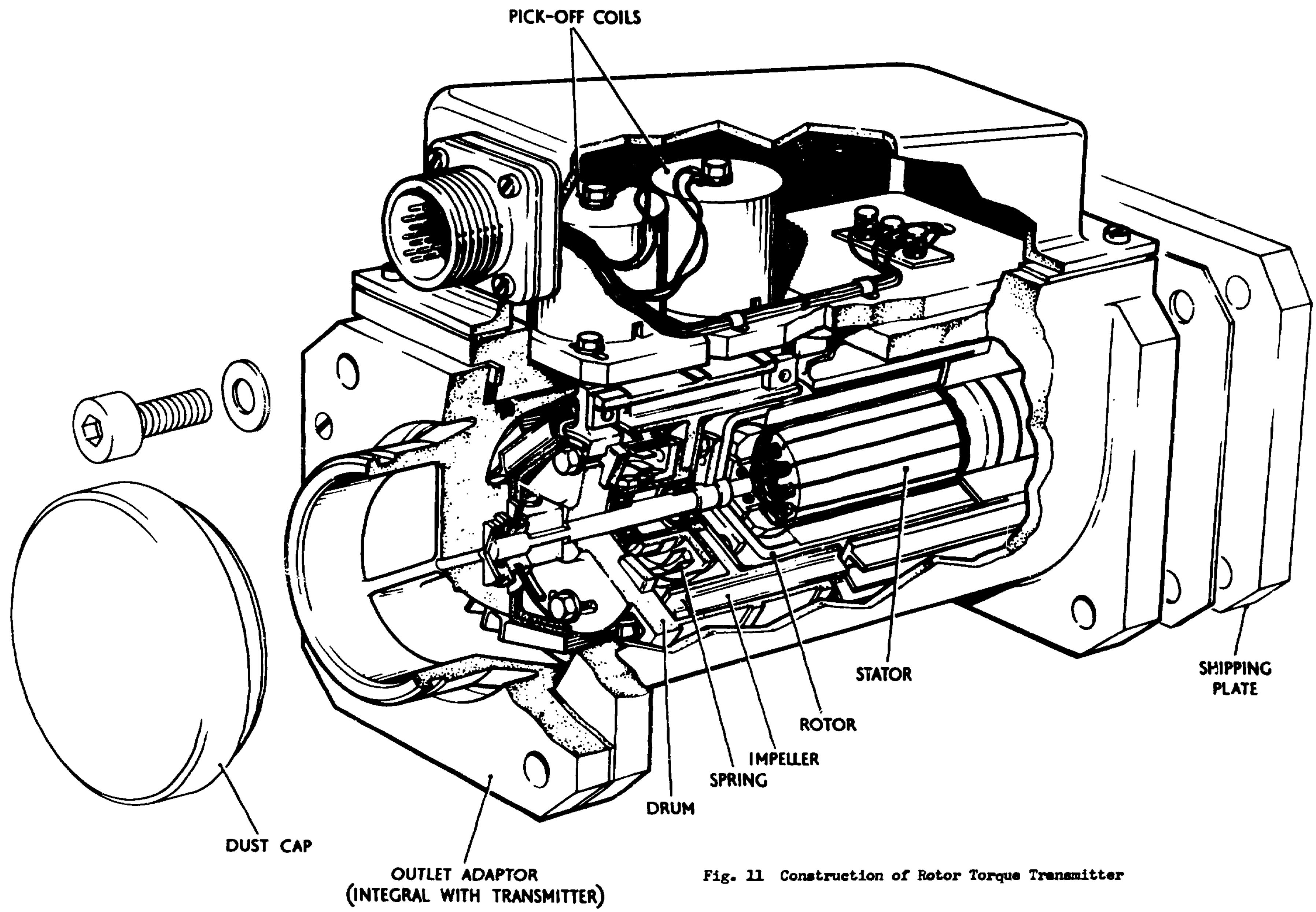


Fig. 11 Construction of Rotor Torque Transmitter

(c) Turbine Drive

If the electrical drive is replaced by a turbine drive unit extracting energy from the fuel, then no external power source is required and the weight of the installation can be reduced.

The turbine is a helical type of relatively low efficiency, low pressure drop and simple construction. It is situated at the inlet end of the transmitter, prior to the straightening vanes, and is locked onto the drum of the measurement assembly by extending the measurement assembly shaft along the entire length of the transmitter.

A substantially constant speed of rotation is achieved by means of a spring loaded by-pass valve placed in parallel with the turbine. At the lowest flow rate all fuel is passed through the turbine to obtain the desired rotational speed but as the flow rate increases the build up of pressure across the turbine progressively opens the by-pass valve and creates an additional flow path.

There is obviously a minimum flow, below which the turbine will not rotate at a satisfactory speed. Recent work has shown that with a system capable of operation at flow rates up to 10,000 Kg/hr it is possible to obtain satisfactory performance with flow rates as low as 50 Kg/hr.

The transmitter output is provided by two pick off coils, each of which consists simply of a large number of turns of copper wire wound on a high temperature bobbin which is mounted on a soft iron core. One coil produces a pulse when the magnet on the drum assembly passes beneath it, the other senses the magnet on the impeller. The amplitude of the pulses is of the order of 1V peak to peak and the repetition period is 0.3 sec.

4.3.3 Transmitter Performance

4.3.3.1 Accuracy

As this transmitter measures mass flow rate directly, no allowance is needed for ancillary sensing equipment such as density correctors or temperature probes, and in theory changes in fuel temperature or density will not affect the accuracy of the device. In practice errors arise from two significant areas namely:

(a) All the fuel does not pass through the measurement assembly, or alternatively under low flow conditions may pass through the measurement assembly more than once.

(b) Changes will occur in the torque/deflection curve of the impeller drive spring.

It is not possible to ensure that all the fuel passes through the measurement assembly as there must be some leakage due to the clearance between the rotating drum and the body of the transmitter. This effect can be minimised by reducing clearances and differential expansion to a minimum, and in addition the error at normal room temperature is eliminated when calibrating the transmitter. With changes of fuel temperature however some differential expansion within the transmitter occurs, and also with changes in the viscosity of the fuel the leakage rate will be affected.

At low flow rates the eddy currents which occur at the leading edges of the impeller vanes cause fuel which has entered the measurement assembly to leave it against the direction of flow and then re-enter the assembly. As the fuel must be accelerated more than once positive errors will be introduced. With increasing flow rates these eddy currents occur within the impeller and no errors are introduced. The effects can be reduced by careful design of the impeller and by reducing the speed of rotation of the measurement assembly.

When considering the angular velocity of the measurement assembly a compromise between accuracy at the extremes of the flow range must be considered. As explained above, too high a velocity will introduce errors at the low flow rates, whilst too low a velocity causes a negative error at high flow rates due to the effect that all of the fuel passing through the impeller is not accelerated to the terminal velocity v_y. This latter effect will also occur if the impeller vanes have too short a length.

As described in Section 4.3.2 the calibration spring is manufactured from Ni Span C. All springs for each type of flowmeter are manufactured from the same batch of Ni Span C and are carefully heat treated to give a temperature coefficient which will compensate for any other temperature sensitive changes that occur within the transmitter, such as increase in the radius of gyration of the impeller with increasing temperature, and increased leakage past the drum with reduction in fuel viscosity.

Early problems with the stability of Ni Span C have now been overcome and good repeatability has been obtained from transmitters which have achieved tens of thousands of hours of aircraft operation.

Calibration limits for a modern rotor torque transmitter are shown in Figure 12. The transmitter has been designed to meet the requirements of a modern high performance engine having a maximum flow rate of 10,000 Kg/hr and fuel temperatures ranging from -10°C to +130°C. Performance is quoted for normal fuel temperatures (30°C to 100°C) which will apply over the vast majority of flight conditions, whilst a relaxed performance is quoted for extreme fuel temperatures (-10°C to 30°C and 100°C to 130°C). Transmitters are now available which will operate satisfactorily with fuel temperatures from -40°C to +180°C.

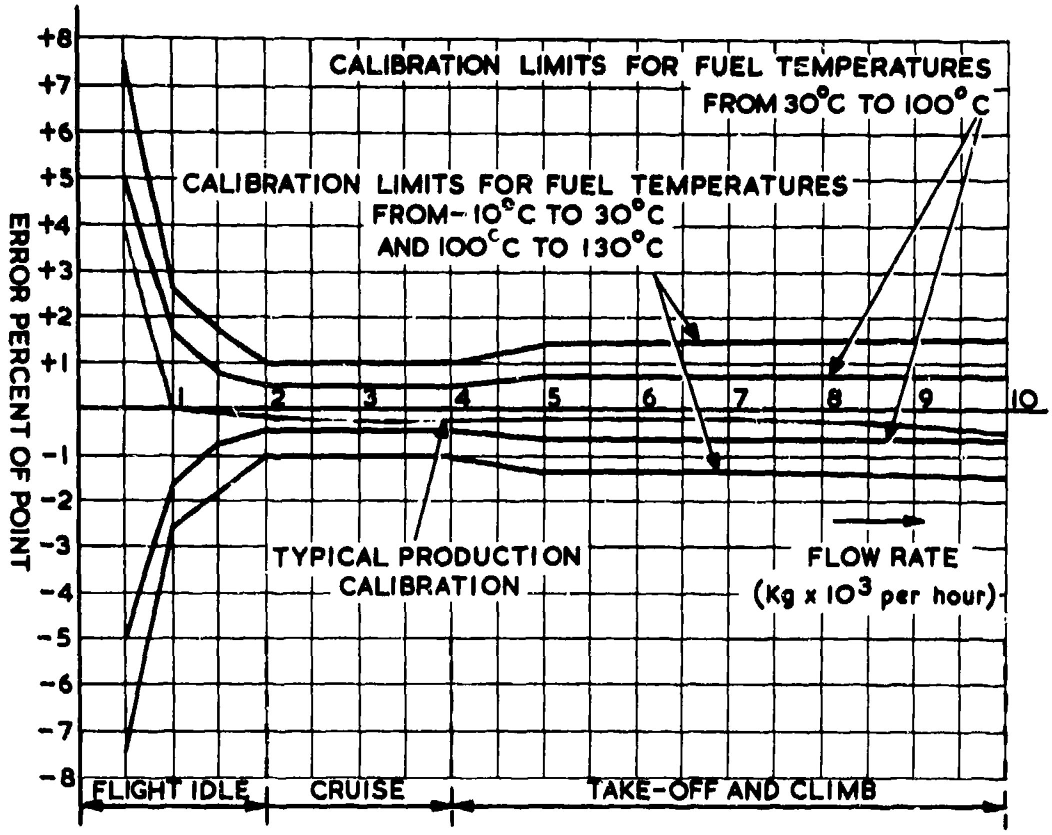


Fig. 12 Calibration Limits for Rotor Torque Transmitter

Reference to Figure 12 shows that an accuracy of better than 0.5% of point can be achieved over the 'cruise' range for normal fuel temperatures, whilst under adverse conditions this increases to ± 1% of point. Calibration requirements are relaxed in the 'take-off' and 'flight idle' portions of the flow range.

Also shown in Figure 12 is a typical production acceptance test result. This test indicates clearly the errors discussed above which occur at the extremes of the flow range. By shaping the leading edges of the blade of the impeller, or by increasing the number of blades, the error at the low flow rates can be significantly reduced, but in practice an aircraft spends very little time under these conditions of low flow rate and the added complexity and cost of carrying out these improvements is not financially justifiable.

4.3.3.2 Life and Reliability

The transmitter has a simple mechanical construction free from delicate mechanisms, pivots, electronics, etc. and is therefore a rugged reliable device.

If the transmitter is fitted with the 'low speed' motor drive or the turbine drive then the only wearing parts are relatively large ball bearings which rotate at only 100 rpm and which are always immersed in fuel. With these types of drives it is possible for manufacturers to confidently predict a service mean time between failures approaching 40,000 hours.

For transmitters incorporating the 'high speed' motor with its speed reducing gear head the predicted MTBF will be reduced to less than 10,000 hours.

The transmitter will have an ultimate life approaching 50,000 flying hours provided perishable items such as seals are renewed at the recommended periods.

4.3.3.3 Pressure Drop

The pressure drop across the transmitter is determined to a large extent by the inlet and outlet adaptors needed to couple the unit to the existing engine pipe work. However, it can be said that in general transmitters of this type do show a significant advantage over the variable orifice devices and have a further advantage in that the pressure drop does not increase if the unit becomes jammed.

At 10,000 Kg/hr a pressure drop of approximately 2 lb per square inch is achieved.

4.3.3.4 Transient Response

This type of transmitter has severe limitations if transient measurements are required as the flow rate is only sampled twice per revolution of the measurement assembly.

The transmitter described in Section 4.3.2 has a rise time of approximately 80 millisec but the output is only sampled every 300 millisec.

4.3.4 Installation

4.3.4.1 Effects of Flow Conditions

The true mass transmitter shows a significant advantage over other types in that it is far less susceptible to flow conditions, as it is not affected to any significant extent by changes in the velocity profile of the flow or by changes from laminar to turbulent conditions.

The true mass transmitter is, however, like the turbine affected by swirl in the fuel. Although with careful design of the straightening vanes any adverse effects on accuracy can be largely removed, if there is a requirement to achieve the full potential accuracy of the transmitter it is recommended that the transmitter be calibrated when connected to representative pipe work.

4.3.4.2 Calibration Adjustments

No electrical adjustments are necessary to calibrate the transmitter. Instead, rigidly clamped mechanical adjustments are used. Two adjustments outside the fuel area are provided on the assembled transmitter as follows:

(a) Zero shift is adjusted by altering the position of the pick-offs. This can be done while the transmittor is being flow tested and adjusts the transmitter calibration curve up or down a fixod number of Kg/hr.

(b) Swirl shift is achieved by rotating a small rudder in the fuel flow path upstream of the measurement assembly and thus creating a swirl in the fuel. This can be done under flow conditions and changes the transmitter calibration by X% of point/kg/hr, X being determined by the swirl rudder angle presented to the fuel flow.

Swirl adjustment is fuel density conscious and can cause calibration shifts when the fuel density changes with fuel temperature. The shift resulting from a change in fuel density is calculated by multiplying the percentage swirl adjustment introduced at 20°C by the percentage change in fuel density. In most aircraft applications the change in fuel density at extremes of fuel temperature is less than 15% of that prevailing at +20°C. Therefore if the adjustment is restricted to say 1%, the maximum change due to temperature is only 0.15%.

On future transmitters this adjustment may be designed out as part of cost reduction and reliability programmes. Removal of the swirl rudder also enables a further sealing point to be eliminated.

Rate shift is adjusted by altering the effective length of the calibration spring, but it should be noted that spring rate adjustment is not normally necessary after assembly of the transmitter.

4.3.4.3 Aircraft Wiring

The signal from the transmitter is the time displacement between two pulses. The two pulse signals are approximately 1.5 volts peak to peak in magnitude and have a repetition rate of one pulse every 0.3 second. The magnitude of the signal and the slowness of its repetition, relative to other aircraft frequencies, make for a good signal to noise ratio. Shielded signal leads are not required and since the signal carrying the flow rate information is not dependent on pulse magnitude, the effects of any capacitance in the signal leads is not a concern. Also, as the calibration is independent of pulse magnitude mechanical strains on the pick offs due to temperature and vibration which might change the magnitude of the signal have no effect on the transmitter calibration. With increased experience on aircraft installations it has been possible to reduce the signal connections running between transmitter and electronics to three twisted leads.

4.3.4.4 Orientation

Within the transmitter's sensing device, a balance has been established to ensure that the position of the transmitter has no effect on its operation.

The transmitter calibration is inherently insensitive to balance and position as signals are received for each 180° rotation of the measurement assembly and the average of the two signals per revolution is the true calibration regardless of balance or operating position. Balancing is done on the assembly only to limit variation in the two signals.

4.3.5 System Implementation

4.3.5.1 Basic System Signals

Figure 13 shows a block diagram of the fuel flowmeter instruments together with signal wave forms.

As explained in Section 4.3.1 the output from the transmitter consists of two trains of pulses, the time difference 't' between them representing the mass flow rate through the transmitter.

The two trains of pulses are passed into the Pulse Converter, the output of which is rectangular pulses of length equal to 't'.

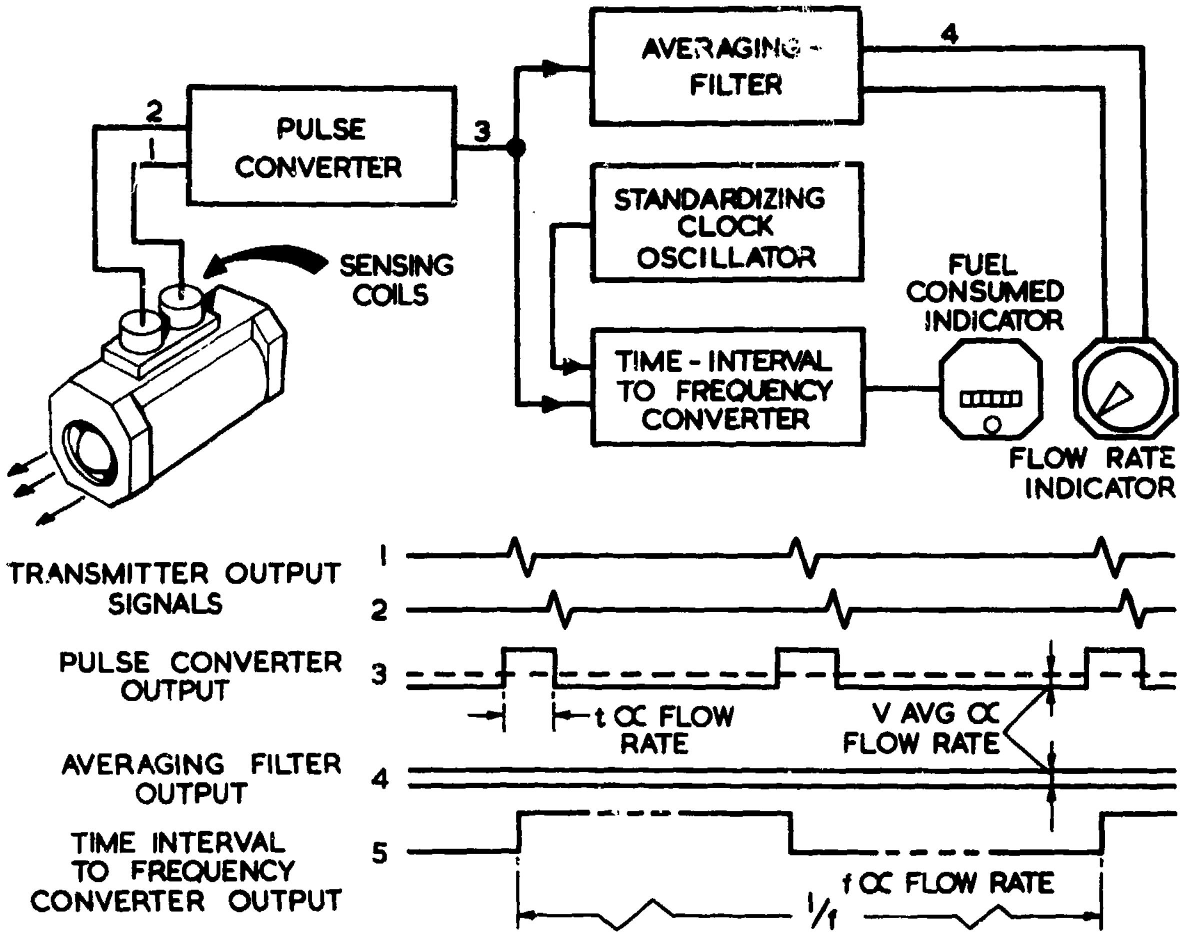


Fig. 13 Basic Signals for True Mass Flowmeter System

In order to display fuel flow rate information in an analogue indicator, the rectangular pulse train from the pulse counter is processed by an Averaging Filter to provide a ripple free D.C. signal to the flow rate indicator. The magnitude of this D.C. signal is proportional to flow rate.

For fuel consumed information, the train of rectangular flow rate pulses from the Pulse Converter and a high frequency train of pulses from the Standardising Clock Oscillator are brought together at the Time-Interval to Frequency Converter. Here the flow rate pulse gates 'on' and gates 'off' high frequency pulses from the Standardising Clock Oscillator. The gated pulses are then frequency divided by bistable flip-flops within the Time-Interval to Frequency Converter, the output of which is a low frequency pulse train (almost square wave) in which each pulse represents a fixed amount of fuel (say 10 Kg). Each pulse causes one step on a stepping motor in the fuel used indicator and as it steps it advances the mechanical counter in the indicator by 1 digit (10 Kg). To reset the counter to zero two leads from the indicator are switched together and this causes an internal reset oscillator to become energised. The signal from this oscillator is used to run the counter backward to zero where a mechanical stop prevents any further travel.

If there is no requirement for aircraft indicators, but it is required to feed the transmitter output into a standard flight test recording system then the basic transmitter signal will require processing. The output from the Pulse Converter is of a form suitable for driving a standard proprietary pulse width measuring counter.

4.3.5.2 Self Test

Experience has shown that approximately 50% of all flowmeter removals from current aircraft are unconfirmed when tested in the laboratory. The true mass transmitter with an electric motor drive unit allows a significant advance to be made in that a high degree of self test can be achieved not only on the transmitter, but on the associated indicators. The unique feature of the self test is that it is possible to check the system with the aircraft engine shut down (i.e. no flow conditions), because the flow transmitter is rotating and supplying output information regardless of engine conditions, provided the aircraft electrical system is energised. The following items may be checked:

(a) Angular velocity of measurement assembly.

(b) Amplitude of drum pulse.

(c) Amplitude of impeller pulse.

(d) Performance of flow rate indicator at a pre-selected flow rate.

(e) Performance of fuel consumed indicator at a pre-selected flow rate.

(f) Aircraft wiring between units.

The flowmeter system shown in Figure 14 features a computer which provides a self test facility.

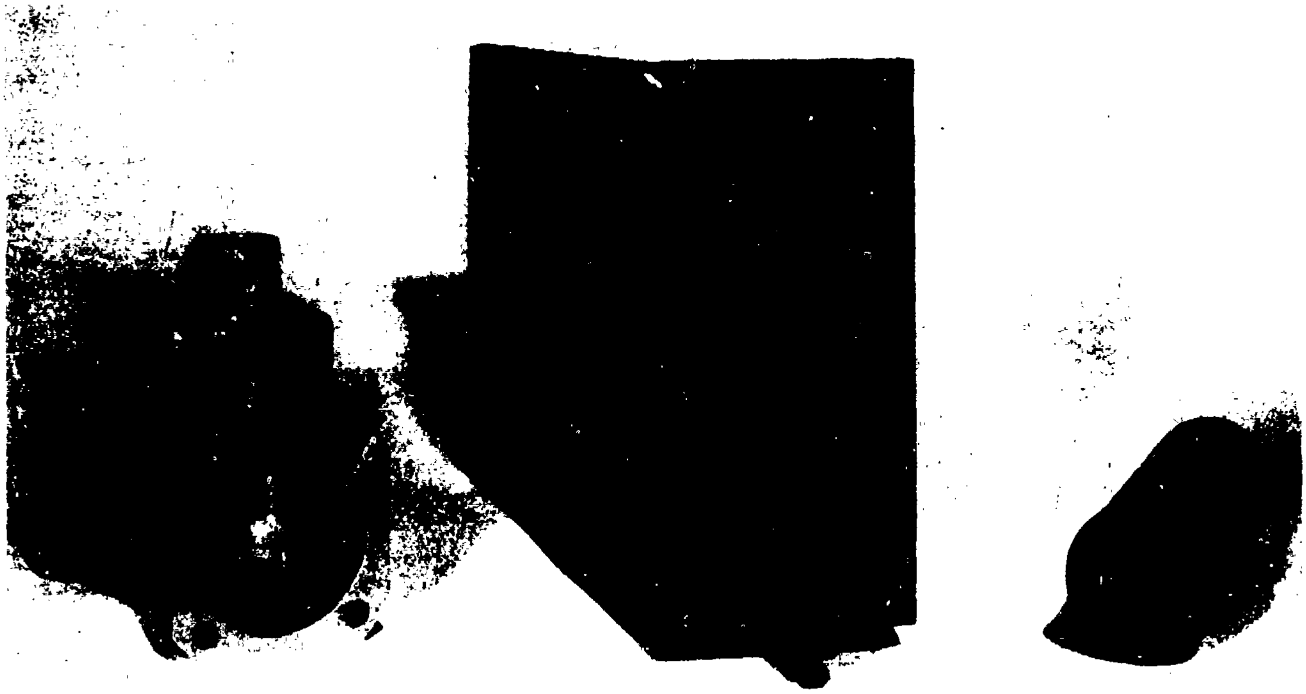


Fig. 14 True Mass Flowmeter System
(Approx. [illegible] full size) - Courtesy Electrc Development Corporation

4.3.5.3 System Performance

As the majority of the computing associated with the rotor torque transmitter is digital, and indicators are servo driven, the errors introduced in the computing are minimal and system accuracy is dependent to a very large extent on transmitter accuracy.

Utilising the transmitter accuracies quoted in Section 4.3.3.1 a typical system accuracy will be as follows:

Operating Conditions	Flow Rate Error %	Fuel Consumed Error %
Normal	0.9	0.5
Adverse	1.3	1.0

The error in displaying flow rate is larger than that for fuel consumed as the signal is of an analogue rather than a digital form. With digital display of flow rate errors comparable with those of fuel consumed can be achieved.

Figure 14 shows a True Mass Flowmeter System employing an electronics package. This package contains the computing and self test circuitry covering four engine channels. The flow rate indicator is not shown.

4.4 Comparison of Performance of Stator Torque and Rotor Torque Flowmeters

Comparison of performance data for stator torque and rotor torque transmitters indicates that neither shows a significant advantage over the other. Both are capable of achieving accuracies of approximately 0.5% over the cruise range and performance at the extremes of the flow range are dependent on the amount of mechanical refinement that is financially justifiable.

Consider the three major sources of error listed for the rotor torque transmitter in Section 4.3.3.1:

(a) Changes in spring torque / deflection curve.

(b) Eddy currents causing fuel to pass through measurement assembly more than once.

(c) All fuel not being accelerated by the measurement assembly.

Any spring effects will apply equally to the stator torque device, eddy currents will affect the spring restrained stator and leakage past the stator will occur. If the stator is too short or the slow rate of the fuel too high then complete deceleration will not take place.

One significant advantage of the rotor torque device is that the bearings on which the measuring element is mounted are subjected to a continuous tumbling motion, due to rotation of the measurement assembly, which drastically reduces friction.

5. COMPARISON OF FLOWMETERS

This section provides a brief comparison of the performance of turbine, variable orifice and angular momentum flowmeters. Such a comparison can only be general and should be treated as such: there is an exception to every rule.

When choosing a flowmeter for a specific application, reference should always be made to the manufacturer of the unit. Obvious dangers such as placing a unit designed for working at low pressures in the high pressure system of an engine are readily apparent, but less obvious problems may arise. Many transmitters employ alloys and gasket seals that lose their strength at the elevated fuel temperatures present on modern high performance engines, and premature failure of one of these components could occur. Another factor often overlooked is the tendency to increase the quantity of additives in aircraft fuels. This again could affect the performance of gasket seals, causing rapid deterioration.

The need to check the performance of any flowmeter on a representative installation cannot be over stressed. All flowmeters are dependent to some extent on the velocity profile of the fuel, cavitation, swirl etc., and a laboratory calibration run using a representative installation, prior to fitting to the aircraft is highly desirable.

The following table summarises typical performance figures, under 'normal' conditions, of the three types of flowmeter discussed in the previous chapters. For general aircraft use the true mass angular momentum transmitter offers significant advantages and this is reflected in its growing popularity. For flight trials work, however, the turbine offers a slightly better accuracy and has a significant advantage for transient measurements. The advantage offered by the true mass device is that fuel temperature and density measurements are not required. The variable orifice transmitter has little to offer for flight trials work, its importance being as an inexpensive mass system for normal aircraft use.

TABLE 1

	Turbine	Variable Orifice	Angular Momentum
1. Flow Measured	Volume	$\frac{\text{Mass}}{\sqrt{\text{Density}}}$	Mass
2. Additional Measurements to obtain Mass	Density and Temperature	None	None
3. Fuel Used Accuracy - Normal A/C Use			
Basic Transmitter	±2.0%	±1.3%	±0.5%
Density Measurement	±0.5%	Included above	Not required
Temperature Measurement	±0.2%	Included above	Not required
Computing	±0.5%	±0.8%	±0.2%
Mass Measurement (R.S.S. Addition)*	±2.1%	±1.5%	±0.5%
4. Accuracy Using Flight Trials Methods			
Transmitter Repeatability over Temperature Range	±0.2%	±0.7%	±0.3%
Density Measurement	±0.1%	Included above	Not required
Temperature Measurement	±0.1%	Included above	Not required
Mass Measurement (RSS Addition)*	±0.2%	±0.7%	±0.3%
5. Typical Pressure Drop at 10,000 Kg/hr	1 lb/in^2	4 lb/in^2	2 lb/in^2
6. Time Constant	10 millisec	50 millisec	Output sampled every 300 millisec

* 'RSS Addition' is addition taking the square root of the sum of the squares.

6. CALIBRATION TECHNIQUES

6.1 Introduction

Commonly used techniques for transmitter calibration are:

(a) A primary flow standard.

(b) A secondary flow standard.

(c) A master transmitter.

A brief description of the three methods follows together with their main advantages and disadvantages.

As stressed in previous chapters calibration runs should always be carried out using representative pipework unless the transmitter is fitted with efficient flow straighteners.

6.2 Use of a Primary Flow Standard

This method is normally used where accuracy is of prime importance, ± 0.1% of actual flow rate being achievable with care.

For the calibration of flowmeters to a high order of accuracy in gravimetric units it is generally accepted that the use of primary flow standard taking measurement of time and weight is the best method. Using this technique the flowmeter is placed in a system whereby the flow rate through the system can be set to any desired value and held constant. Measurement of this flow rate is obtained by collecting a mass of fuel in a weigh tank over a period of time. During the same period of time measurements of the output of the flowmeter under calibration are taken and compared with the flow rate established by dividing the mass of fuel weighed by the time taken to weigh it. There are in turn two methods of time and weight measurement.

1. Dynamic weighing

2. Static weighing

In the former the weighing operation automatically triggers the timing mechanism and thus the weighing operation is carried out simultaneously with the timing operation. In the latter the timer is used to operate valves or shutters to enter or by-pass the fuel to the weighing tank. Both techniques suffer from certain disadvantages and in general it becomes a matter of individual preference as to which method is chosen especially if a high or low temperature capability is required. The time and weight method of flow measurement virtually eliminates errors due to changes in specific gravity or viscosity of the calibrating medium. However both methods suffer from the common disadvantage that the calibrating sequence is more complicated and time consuming than the alternative methods described below.

If volumetric measurements are required then either fuel density must be measured or the weighing mechanism can be replaced by a calibrated vessel. The time over which the measurement is taken is arranged so that the volume of fuel measured is approximately constant whatever the flow rate. The cross sectional area of the collecting vessel is arranged to be small at the point where the required volume has been collected so that any changes in volume will appear as a large change in height of the free surface of the fuel, and the volume collected can be accurately determined.

6.3 Use of a Secondary Standard

Secondary standards take the form of simple and basic flow meters which are less cumbersome to use than the primary standards. Secondary standards are usually checked against primary standards on a routine inspection calibration basis. The most commonly used is the Rotameter which is a variable orifice device capable of giving an accuracy of ± 0.2% of true flow rate (Ref. 5).

The instrument consists of a metal float free to move inside a vertical tapered glass tube, the cross section of the tube being at a minimum on its base. The fuel flows upwards through the tube and lifts the float, which is denser than the fuel, until equilibrium is established where the pressure drop across the float is balanced by the weight of the float in the fuel.

By measuring the height of the float in the tube, the flow rate can be obtained.

The basic equation of this type of calibrator is:

$\dot{M} = CA\sqrt{h\rho}$

$\dot{M}$ = Mass flow rate

C = Discharge coefficient of the annular orifice

A = Area of annular orifice

h = Pressure drop across float

ρ = Density of fuel

It can be seen that the mass flow indication is sensitive to changes in fluid density, also variation in fluid viscosity can cause measurement errors due to changes in the discharge coefficient K. The float design is empirically adjusted to compensate for changes in viscosity associated with those changes in temperature encountered in normal temperature controlled systems.

6.4 Use of a Master Transmitter

Master transmitters are mainly used in production organisations where there is a requirement for rapid calibration techniques. Facilities for periodically checking the performance of the master transmitter must be available. It is good practice for the master transmitter to be the same type as the unit under test as discrepancies which may arise due to changes in fuel characteristics, temperature, etc. will then tend to affect the master transmitter in the same way as the unit under test. It is common practice to compare the output of the calibration transmitter and the unit under test using automatic or semi automatic test equipment.

The accuracy of this method is determined by the repeatability of the master transmitter.

7. FUTURE DEVELOPMENTS

7.1 Introduction

Virtually all present day aircraft fuel flow measuring applications are covered by the three types of transmitter described in previous chapters. Other mechanical transmitters have been designed, such as the gyroscopic mass flowmeter and the constant displacement pump flowmeter (Ref. 5), but have had little or no practical application in the aircraft field. The major area which does however look promising is solid state flowmeters, as by deleting all moving parts it should be possible to increase the reliability of the transmitter significantly, and by reducing the obstructions in the flow path the pressure drop will be reduced. The most common types of solid state flowmeter are discussed below, together with the Drag Plate Transient Flowmeter, a device which may meet specialist requirements for measuring rapidly changing flows.

7.2 The Magnetic Flowmeter

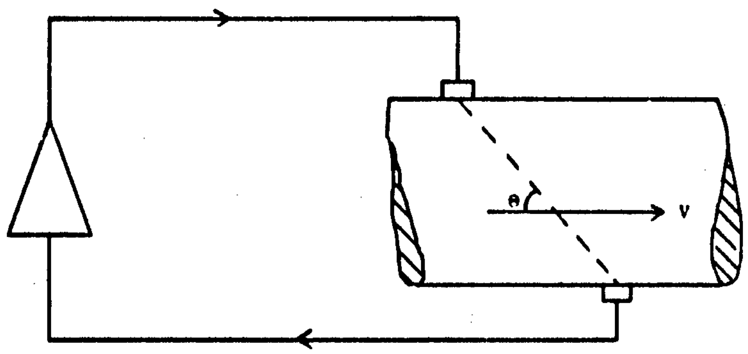
The Magnetic flowmeter is an extremely simple device which involves establishing a magnetic field at right angles to the direction of flow across the pipe carrying the fluid to be metered (Ref.5).

The meter is a practical proposition, being used in certain industrial applications, but unfortunately an inherent requirement of the device is that the fluid must be an electrical conductor and it has not yet been successfully adopted for aviation fuel which is a poor conductor.

7.3 The Ultrasonic Flowmeter

This method involves measuring the velocity of the fluid through a pipe line using ultrasonic pulses. To measure the velocity the 'sing-around' system is used; a pulse of ultrasound leaves the transmitter transducer and travels through the liquid to the receiver.

This receiver signal causes the transmitter to emit a second pulse and thus a 'sing-around' frequency is set up in the circuit which is a function of the path length and the velocity of sound in the liquid.



If the liquid has a velocity V the 'sing-around' frequency is modified due to the increase in the effective sound velocity.

$$f_1 = \frac{C + V \cos\Theta}{d}$$

where C = Velocity of sound in liquid

d = Distance between transducers

By using a second pair of transducers transmitting on the opposite path to the first, i.e. transmitter downstream, one gets a second frequency measurement.

$$f_2 = \frac{C - V \cos\theta}{d}$$

Using suitable mixing circuits one thus obtains readings of C and V.

This method of velocity measurement has inherent inaccuracies due to differences in the path lengths and temperature gradients within the liquid affecting the velocity of sound in each path.

A new and sophisticated method of overcoming these problems is to use one pair of transducers transmitting in each direction simultaneously by time multiplexing the signals. This system is fully discussed in a paper by Loosemore and Muston (Ref. 6).

Density is measured using an acoustic impedance detector which is an ultrasonic transducer, operating at resonance, fed by a constant current oscillator. Under such conditions the voltage output of the oscilla... is directly proportional to the product of the density and the velocity of sound in the liquid. As the velocity of sound is one of the quantities measured in the first part of our system density can readily be computed.

The ultrasonic flowmeter offers the advantages that it is non constrictive, has no internal moving parts, surging and overloading cannot cause damage, it is unaffected by attitude, acceleration or inertial forces and is independent of electrical conductivity of fluid. The major disadvantages are that it is dependent upon velocity distribution within the pipe and the electronics are more complex than with conventional flowmeters. Development is being concentrated in this latter area, where the problem is already becoming of less significance with the rapidly increasing availability of Large Scale Integrated circuits.

7.4 The Thermal Flowmeter

A thermal flowmeter working on the well established principle of continuous calorimetry has been developed by Contactrol Limited, Harrietsham, Kent.

The flow transducer consists of a heater resistance situated in a thermally insulated duct with temperature sensitive semiconductors situated upstream and downstream of the heater resistance. The differential temperature signal from the upstream and downstream transducers is applied to a differential amplifier which controls the power supplied to the heater, the amount of power being adjusted to give a fixed temperature differential across the sensors. The power supplied to the heater is proportional to the mass flow rate through the meter.

This device has been found to have a linearity of $\pm$ 2% for flow rates up to 20 Kg/hr. For higher flow rates a by-pass method must be adopted.

7.5 The Drag Plate Transient Flowmeter

This flowmeter has been developed by the National Engineering Laboratory for a specialist commercial application where the requirement is for a rapid response time with a fluid at high pressure and high temperature. (Ref. 7.) The possibility of adapting it for aircraft use is now under consideration.

The flowmeter contains a thin perforated disc, or drag plate, which is mounted on a rod normal to the direction of flow. Changes of flow rate produce forces which deflect this drag plate and the supporting rod which is restrained by a torsional hinge. The deflection is measured by an E-core pick off mounted on the end of the rod remote from the drag plate.

The flowmeter described has a response time of less than 10 millisecs and a pressure drop of 0.02 lb/in^2 at the maximum flow rate of 6,000 gal/hr. Before use the meter requires to be set up under working conditions of pressure and temperature and with zero flow, and is therefore unlikely to be of use for general aircraft applications, but it may find a use in flight test work in transient measurement.

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